
Mars Science Laboratory

Visual Odometry (VO)

Technology Test Report

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Prepared by:

Terry Huntsberger

Testing Team:

Terry Huntsberger
Hrand Aghazarian
Mike Garrett
Lee Magnone
Gail Woodward

CLARAty Support:

Max Bajracharya

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Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109-8099

Signature Sheet

Approval:

Terry Huntsberger, Task Manager

Richard Volpe, Mars Technology Program Office

Charles Whetsel,

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Auxiliary Documents

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VO FDD	03/28/2003	Document # TBD
VO Test Plan	09/05/2003	Document # TBD
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VO Test Report

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Executive Summary

Algorithm Background

The VO (visual odometry) algorithm is designed to estimate heading and position based on analysis of pairs of images combined with rover state information (in the case of these tests the only input was wheel odometry and IMU). The documents related to visual odometry are given in Table 1.

Table I. Related Documents

Larry Matthies “Dynamic Stereo Vision”, PhD Thesis, CMU-CS-89-195
C. F. Olson, L.H. Matthies, M. Shoppers, and M. Maimone, Robust stereo ego-motion for long distance navigation, In <i>Proceedings of the IEEE Conference in Computer Vision and Pattern Recognition</i> , Vol. 2. 2000.
C. F. Olson, L.H. Matthies, M. Shoppers, and M. Maimone, Stereo ego-motion improvements for robust rover navigation, In <i>Proceedings of the IEEE International Conference on Robotics and Automation</i> , pages 1099-1104, 2001.

The algorithm flow is shown in Figure 1. A pair of stereo images is taken into the system at each step that the rover takes, and 3D position of the features are found in the images. The features are then matched to those acquired in the next pair of images using tracking, stereo matching, and a feature rigidity test. Outliers are rejected using a statistical Schonemann test.

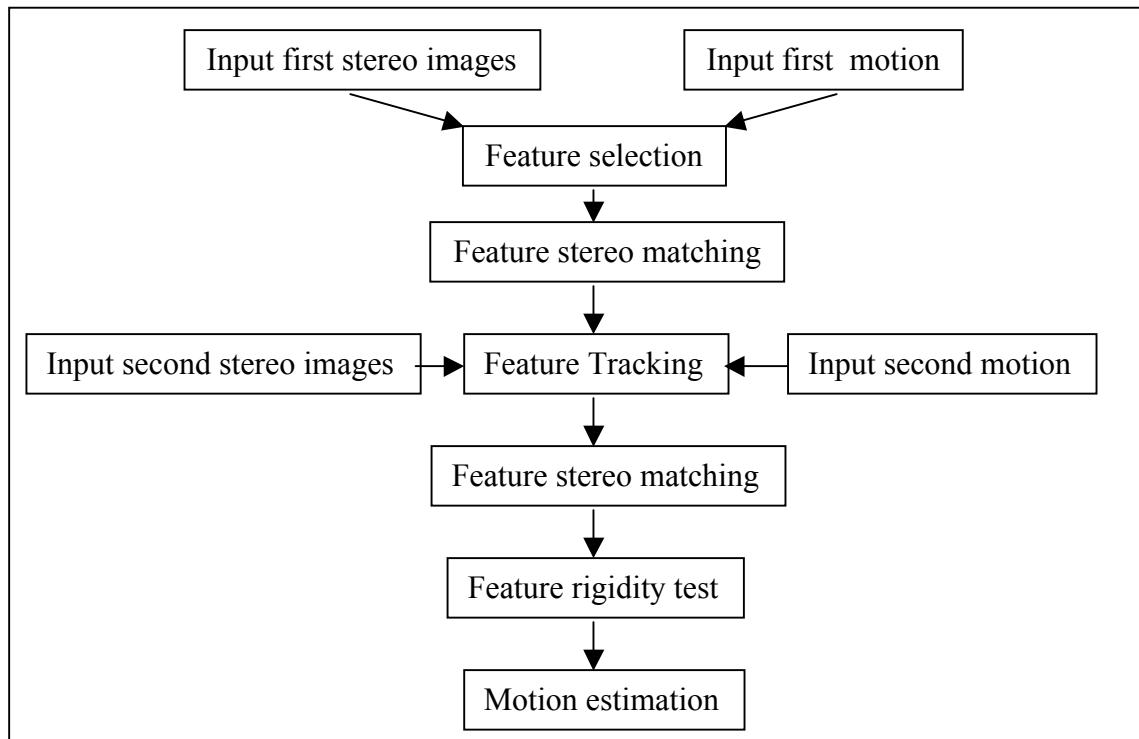


Figure 1. Block diagram of visual odometry (VO) algorithm flow.

Overview

The test and validation of the visual odometry (VO) technology algorithm on the FIDO rover under the CLARAty system was conducted from September 15, 2003 to November 3, 2003 for the field runs in the MarsYard and the Arroyo Seco at JPL, and from November 15, 2003 to April 18, 2004 for the offline analysis. This report compares the results of an onboard implementation of the algorithm under CLARAty for the field, and an offline version of the MER VO algorithm that uses a parameter file for settings at algorithm initialization. The **MER parameter settings** were obtained from Yang Cheng and **serve as the baseline for algorithm performance evaluation**. All tests were run in a relatively benign area of the MarsYard (SW quadrant) and a mixed terrain area of the Arroyo Seco. A total of 24 tests were run to determine algorithm performance for localization accuracy during straight-line and arc drives, turns-in-place, and drives/turns that simulate obstacle avoidance. The original test plan was designed to test the individual parameters of the VO algorithm in isolation and finally in coordination. The test procedure was modified due to the inability of the current CLARAty codebase to run from a configuration file (addressed in the current release of the VO technology algorithm under CLARAty), so the tests were supplemented by off-line runs of the MER VO algorithm which uses an input configuration file to set algorithm parameters. All of the configuration files used for the tests are given in Appendix A. During the course of testing, the MER offline code using the default MER settings obtained from Yang Cheng for the configuration file was found to fail for runs in the Arroyo Seco. A sensitivity analysis was run on the parameters in order to derive settings that address these failure modes. Due to the large number of parameters used for the VO algorithm (~32), the sensitivity analysis was limited to a subset of 17 parameters which are detailed later on in this report. These test-derived parameters thus can not be considered to be an optimal set.

The tests that were run are detailed in the VO Test Matrix below and were performed to **compare the behavior of the VO algorithm with respect to the current MSL reference mission baseline of a localization error of 3% with respect to the total distance traveled**. All results were compared to ground truth data that was collected by a Leica TCRA1103+ TotalStation (rated accuracy of 2mm at 10m range). The test setup is shown in Figure 2, where the FIDO rover has four prism reflectors (one on each corner of the rover) that are used for range and rover attitude determination each time before and after the tests. This setup allows us to extract both position and heading information. All tests were run using the current version of the JPL Stereo code with the FIDO hazard camera calibration files found in Appendix B.

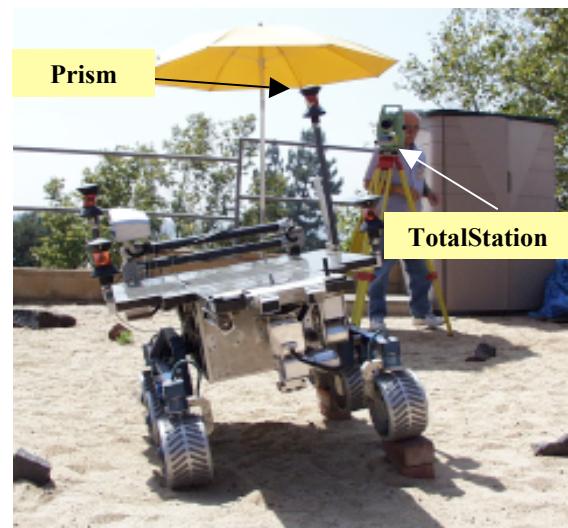


Figure 2. VO test setup. Leica TotalStation is in background and FIDO rover with four prism reflectors is in foreground.

VO Test Matrix

Case #	Description	Objectives
Single Parameter Tests (SPT)		
1.1	Pitch 5°	Test pitch DOF
1.2	Pitch 10°	Test pitch DOF
2.1	Roll 5°	Test roll DOF
2.2	Roll 10°	Test roll DOF
2.3	Roll 20°	Test roll DOF
2.4	Roll 30°	Test roll DOF
3.1	Yaw 5°	Test yaw DOF
3.2	Yaw -10°	Test yaw DOF
3.3	Yaw 20°	Test yaw DOF
3.4	Yaw -30°	Test yaw DOF
3.5	Yaw -45°	Test yaw DOF
4.1	Drive 0.1 m, 0.01 m step size	Test X DOF
4.2	Drive 0.5 m, 0.05 m step size	Test X DOF
4.3	Drive 1 m, 0.10 m step size	Test X DOF
4.4	Drive 2 m, 0.2 m step size	Test X DOF
4.5	Drive -3 m, 0.3 m step size	Test -X DOF
4.6	Drive 4 m, 0.4 m step size	Test X DOF
4.7	Drive 4 m, 1.0 m step size	Test X DOF
4.8	Drive 4 m, 2 m step size	Test X DOF
4.9	Drive 4.5 m, 1.5 m step size	Test X DOF
4.10	Drive 2.5 m, 1.25 m step size	Test X DOF
5	Tests not performed - no software capability	Test Y DOF
6.1	Lift 0.27 m, 0.03 m step size	Test -Z DOF
6.2	Lift 0.24 m, 0.06 m step size	Test -Z DOF
Short Range Navigation Tests (SRNT)		
1	Zig-Zag Drive (Not performed due to substitution of LRNT.3)	Test forward drive with simulated obstacle avoidance movement
2	Square Drive (0.2 m step size)	Test return to origin with drive over square course 1 meter on a side
3	S-Arc Drive (0.2 m step size)	Test forward drive with two short sequential arcs
Long Range Navigation Tests (LRNT)		
1	Straight Drive – Level (0.2 m step size)	Test straight forward drive over level terrain
2	Straight Drive – Mixed Slope (0.2 m step size)	Test straight forward drive over mixed terrain
3	Zig-Zag Drive (0.2 m step size)	Test forward drive with simulated obstacle avoidance movement

The tests were broadly broken down into three categories shown in the VO Test Matrix above. These are **Single Parameter Tests** (SPT) designed to test the VO algorithm performance for the 6 DOF (degrees-of-freedom) of the rover (roll, pitch, yaw, X, Y, Z), **Short Range Navigation Tests** (SRNT) to test the localization performance for short traverses in benign terrain (MarsYard), and the **Long Range Navigation Tests** (LRNT) to test to the localization performance for traverses in terrain that has higher slip rates due to slopes and a rock-field (Arroyo Seco). Test results are reported for the onboard version of the VO algorithm running under CLARAty on the FIDO rover (listed as Onboard in the summary tables to follow), and the offline version of the MER FSW (flight-software) code using the MER default and test-derived settings for the parameter file (listed as Offline MER and Offline Test-Derived respectively in the summary tables to follow).

Table II is a summary of the test results labeled with *Passed*, *Marginal*, and *Failed* ratings. For the tests that involve traverses (SPT4.1-SPT4.10, SRNT2-SRNT3, LRNT1-LRNT3), the localization error ratings are: *Passed* meets the 3% MSL requirement, *Marginal* is between 3% to 6%, and *Failed* is greater than 6%. For all other tests, the ratings of *Passed* and *Failed* are used to respectively indicate where the algorithm returns or fails to return a result. These other tests were used to determine bounds on rover state change that can be tolerated between image acquisition steps.

Traverse Tests

The traverse tests were designed to test the VO algorithm performance with respect to the current MSL baseline requirement after a traverse of a 3% localization error with respect to the total distance traveled. Table III lists the average localization error as a percent of the total distance traveled over all traverse tests (SPT4.1-SPT4.10, SRNT2-SRNT3, LRNT1-LRNT3). The Table also shows results for the average localization error on tests with step-sizes of 0.1 to 0.4 meters between image acquisition, which would be those more typically used in a mission for obstacle detection and path planning for obstacle avoidance. **The average Offline Test-Derived VO localization error with smaller step-sizes (0.1 m to 0.4 m) is within the 3% MSL requirement.** Table IV lists the relative contribution of the down-range and cross-range components of the localization errors over all traverse tests. **The majority of the localization error (62% and 76% respectively for the Offline MER and Offline Test-Derived) can be attributed to the down-range error.** A detailed analysis of the traverse data revealed a growing error over a traverse in the VO estimated Z (height) component of the rover (plots for LRNT1-LRNT3 follow in the individual test results section). This is currently unable to be explained, and the current hypothesis is that it may be due to a very slight pointing vector error in the camera models. Table V lists the average down-range and cross-range errors in meters over all traverse tests.

Chart 1 is a test-by-test plot of the localization error for all of the traverse tests. The first ten tests have been sorted by step-size, and an examination of Chart 1 reveals that the **localization error decreases up to a step size of 0.4 m** and then quickly increases with a

step size of 1.0 m. Further studies using 0.2 m step-size datasets sub-sampled for every third frame (equivalent to a step-size of 0.6 m) have a localization error of 12.2%. We were not able to emulate a 0.5 m step-size using the available data at this time.

Chart 2 shows a scatterplot of the down-range and cross-range errors reported by VO vs TotalStation (Ground Truth) for all of the traverse tests. There is a bias in the errors to an underestimation in the down-range (traced to the overestimate of Z mentioned previously) and more or less no bias in the cross-range error, with the exception of the Onboard algorithm where there is a bias to the left due to the large cross-range error in the LRNT1 run.

Chart 3 shows a plot of the heading errors from VO vs TotalStation (Ground Truth) for each of the traverse tests. The average heading error for all of the traverse test is listed in Table VI. **The average heading error** for the various configuration file parameter settings **is close to zero**, but there are relatively large rms (root-mean-square) errors.

Two test variables that could influence localization error are the step-size and total distance traversed. Charts 4 and 5 plot the localization error vs. these two variables over all of the traverse tests. The trend noted in Chart 1 towards lower localization errors for smaller step-sizes is also seen in Chart 4, but a wider range of error is evident. In addition, the localization errors associated with longer step-sizes may be misleading since the VO algorithm defaults to odometry/IMU when failing to find feature matches across images. This is most apparent in the 2 m step-size case, where the Onboard and Offline MER parameter settings caused the algorithm to fail and default to odometry/IMU, whereas the Offline Test-Derived parameter settings matched features but with a large percent error. This could be a problem in the field since **the rover must know when not to trust the VO output and default to odometry/IMU** instead. Chart 5 shows that although there were not a large number of long traverses (> 5 m), the localization error was not growing and was primarily due to the down-range error caused by the rover Z (height) estimation problem. More extensive testing of longer traverses will be needed to verify if this is an element of the VO algorithm behavior.

Table II. Summary of Test Results

Test Case	Description	Test Results		
		Onboard	MER	Test-Derived
Single Parameter Tests (SPT)				
1.1	Pitch 5°	Passed	Passed	Passed
1.2	Pitch 10°	Failed	Failed	Passed
2.1	Roll 5°	Passed	Passed	Passed
2.2	Roll 10°	Passed	Passed	Passed
2.3	Roll 20°	Passed	Failed	Passed
2.4	Roll 30°	Failed	Failed	Passed
3.1	Yaw 5°	Passed	Passed	Passed
3.2	Yaw -10°	Passed	Passed	Passed
3.3	Yaw 20°	Passed	Failed	Passed
3.4	Yaw -30°	Passed	Failed	Passed
3.5	Yaw -45°	Failed	Failed	Failed
4.1	Drive 0.1 m, 0.01 m step size	Passed	Failed	Passed
4.2	Drive 0.5 m, 0.05 m step size	Marginal	Failed	Marginal
4.3	Drive 1 m, 0.10 m step size	Passed	Marginal	Passed
4.4	Drive 2 m, 0.2 m step size	Marginal	Passed	Passed
4.5	Drive -3 m, 0.3 m step size	Marginal	Passed	Passed
4.6	Drive 3.2 m, 0.4 m step size	Passed	Passed	Passed
4.7	Drive 4 m, 1.0 m step size	Failed	Failed	Failed
4.8	Drive -4 m, 2.0 m step size	Passed	Failed	Failed
4.9	Drive 4.5 m, 1.5 m step size	Passed	Failed	Failed
4.10	Drive 2.5 m, 1.25 m step size	Passed	Failed	Failed
6.1	Lift 0.27 m, 0.03 m step size	Passed	Passed	Passed
6.2	Lift 0.48 m, 0.06 m step size	Passed	Passed	Passed
Short Range Navigation Tests (SRNT)				
2	Square Drive – 1 m Sides	Passed	Passed	Passed
3	S-Arc Drive	Failed	Failed	Marginal
Long Range Navigation Tests (LRNT)				
1	Straight Drive – Benign Terrain	Failed	Failed	Marginal
2	Straight Drive – Mixed Slope Terrain	Passed	Failed	Passed
3	Zig-Zag Drive	Failed	Failed	Passed

Table III. Average Localization Error as Percent of Total Distance Traveled

	Onboard	Offline MER*	Offline Test-Derived
All Traverse Tests	5.56%	9.73%	7.01%
Smaller Step Sizes	5.42%	6.41%	2.77%

*Does not include results from LRNT due to algorithm failure to find any features that tracked between frames.

Table IV. Relative Contributions of Down-Range and Cross-Range Errors to Average Localization Error Over All Traverse Tests

	Onboard	Offline MER*	Offline Test-Derived
Down-Range	58%	62%	76%
Cross-Range	42%	38%	24%

*Does not include results from LRNT due to algorithm failure to find any features that tracked between frames.

Table V. Average Down-Range and Cross-Range Errors Over All Traverse Tests

	Onboard (m)	Offline MER (m)*	Offline Test-Derived (m)
Down-Range	-0.156±0.082	-0.086±0.093	-0.230±0.094
Cross-Range	-0.118±0.084	-0.040±0.049	-0.009±0.017

*Does not include results from LRNT due to algorithm failure to find any features that tracked between frames.

Table VI. Average Headings Errors Over All Traverse Tests

Onboard	Offline MER*	Offline Test-Derived
0.124±1.372°	0.094±1.349°	-1.132±0.811°

*Does not include results from LRNT due to algorithm failure to find any features that tracked between frames.

Rover DOF Tests

The SPT1-SPT3 and SPT6 did not involve movement of the rover, but were designed to determine the VO algorithm performance and sensitivity for various step-sizes. These tests covered the roll, pitch, yaw and Z (height) rover DOFs. The step-size in each DOF was independently varied until the VO algorithm failed to match features across images. Table II contains the summary for this series of tests, with a *Passed* entry indicating a successful match, and a *Failed* entry indicating an insufficient number of matches. Table VII lists the average performance of the VO algorithms for the three groups of parameter settings (Onboard, Offline MER, Offline Test-Derived) with the step-size upper limit shown in parenthesis in the left-hand column. **In summary, the rover DOF tests indicate that roll can be estimated within 0.03° (heavily dependent on the step-size for step-sizes > 22.5°), pitch can be estimated within 0.25°, and yaw within 0.33°.**

Further details can be found in the individual test summaries. The error in the height (Z) DOF is 1.1% which if accumulated over long traverses could contribute to the underestimation of down-range distances discussed in the previous section.

Table VII. Average Errors Over All Rover DOF Tests

	Onboard	Offline MER	Offline Test-Derived
Roll (up to 30°)	-0.030±0.010°*	-0.026±0.009°†	0.487±0.002°
Pitch (up to 10°)	-0.236±0.008°*	-0.077±0.009°†	-0.214±0.001°
Yaw (up to 30°)	-0.318±0.306°	-0.134±0.086°†	-0.338±0.236°
Height (up to 0.5m)	-0.007±0.002m	-0.005±0.001m	-0.004±0.002m

*Failed SPT1.2, SPT2.4

†Failed SPT1.2, SPT2.3, SPT2.4, SPT3.3, SPT3.4

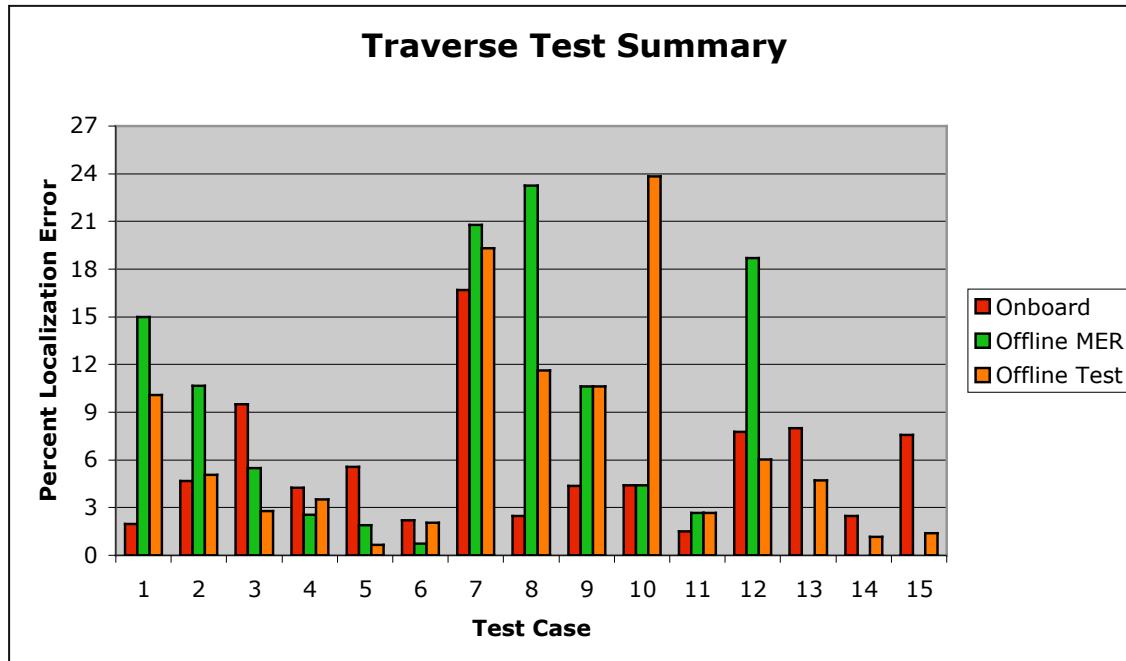


Chart 1. Percent localization error defined as the ratio of the final position offset to GroundTruth over the GroundTruth total distance traveled for all tests that involved traverses. Labels for test cases are in the following table. In tests 13-15 the offline MER code with MER default settings failed to find any features that tracked between frames, so no analysis was possible for those runs.

Chart 1 Horizontal axis labels	
Index	Test Case
Single Parameter Tests (SPT)	
1	4.1: Drive 0.1 m in 0.01 m steps
2	4.2: Drive 0.5 m in 0.05 m steps
3	4.3: Drive 1 m in 0.1 m steps
4	4.4: Drive 2 m in 0.2 m steps
5	4.5: Drive -3 m in 0.3 m steps
6	4.6: Drive 3.2 m in 0.4 m steps
7	4.7: Drive 4 m in 1 m steps
8	4.10: Drive 2.5 m in 1.25 m steps
9	4.9: Drive 4.5 m in 1.5 m steps
10	4.8: Drive -4 m in 2 m steps
Short Range Navigation Tests (SRNT)	
11	2: Drive square 1m on a side
12	3: Drive S-arc path
Long Range Navigation Tests (LRNT)	
13	1: Straight drive - level terrain
14	2: Straight drive – mixed slope terrain
15	3: Zig-Zag drive

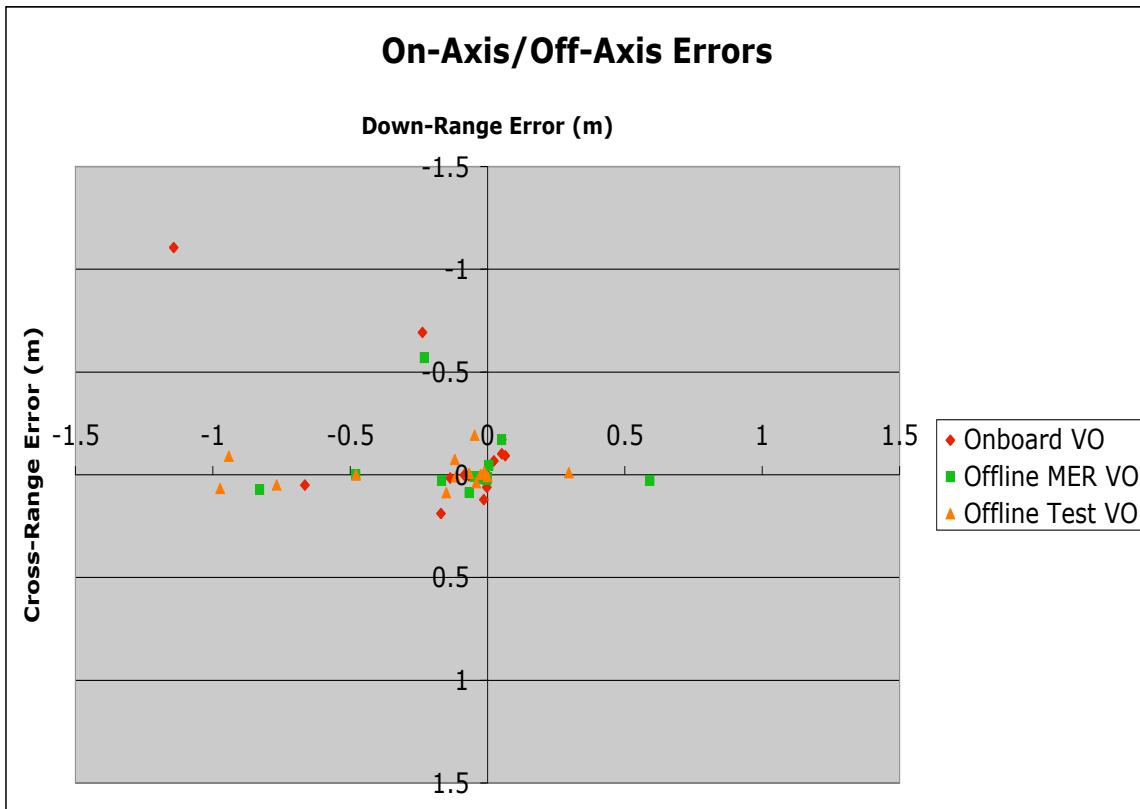


Chart 2. Scatterplot of down-range and cross-range error for all of the traverse tests. Shown are test results derived using the Onboard (red diamond), Offline MER (green square), and the Offline Test-Derived (orange triangle) algorithm parameter sets.

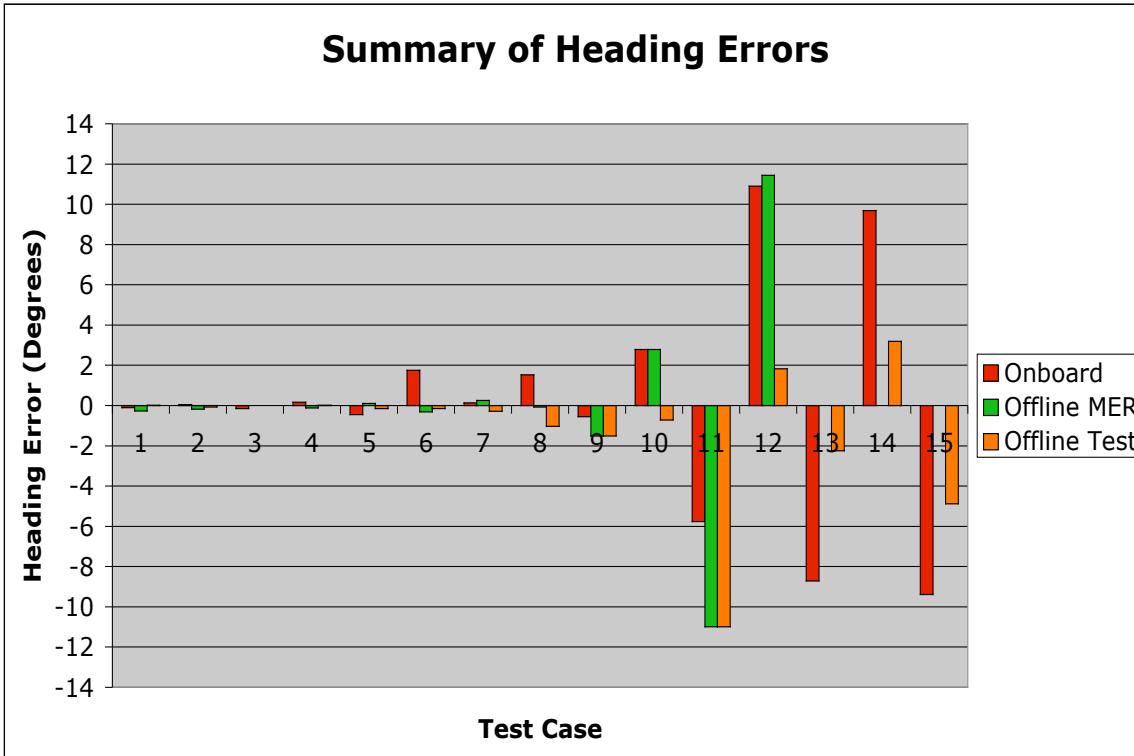


Chart 3. Graph of heading errors compared to GroundTruth for all tests that involved traverses. Indices for test cases are in the following table. In tests 13-15 the offline MER code using the default MER settings failed to find any features that tracked between frames, so no analysis was possible for those runs.

Chart 3 Horizontal axis labels	
Index	Test Case
Single Parameter Tests (SPT)	
1	4.1: Drive 0.1m in 0.01m steps
2	4.2: Drive 0.5m in 0.05m steps
3	4.3: Drive 1m in 0.1m steps
4	4.4: Drive 2m in 0.2m steps
5	4.5: Drive 3m in 0.3m steps
6	4.6: Drive 4m in 0.4m steps
7	4.7: Drive 4m in 1m steps
8	4.10: Drive 5m in 1.25m steps
9	4.9: Drive 6m in 1.5m steps
10	4.8: Drive 6m in 2m steps
Short Range Navigation Tests (SRNT)	
11	2: Drive square 1m on a side
12	3: Drive S-arc path
Long Range Navigation Tests (LRNT)	
13	1: Straight drive - level terrain
14	2: Straight drive – mixed slope terrain
15	3: Zig-Zag Drive

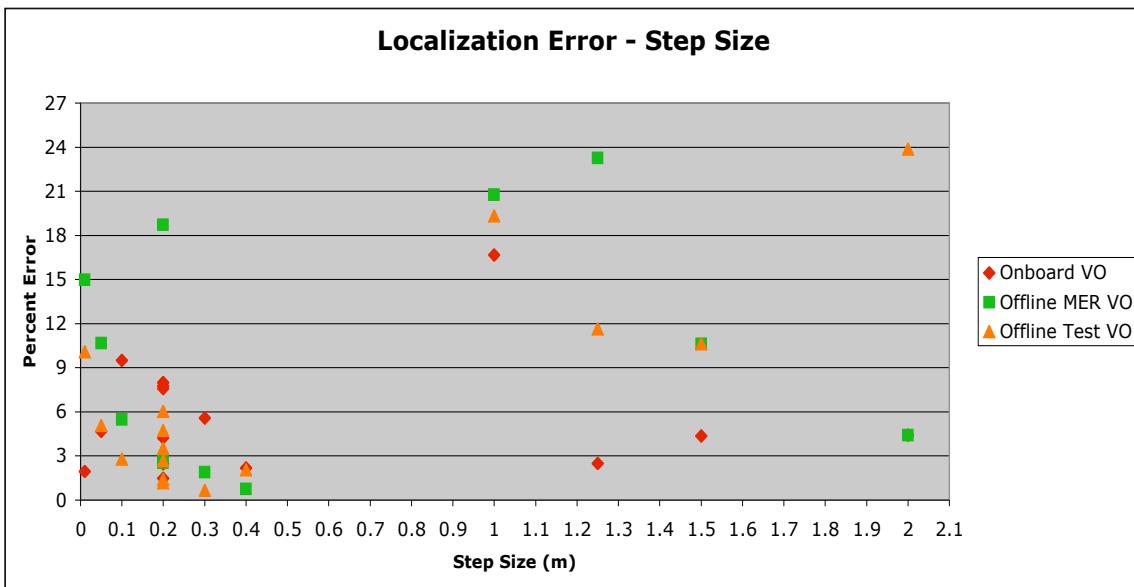


Chart 4. Scatterplot of VO localization error as a percent of the total distance traveled (from groundtruth measurements) versus the step-size over all traverse runs.

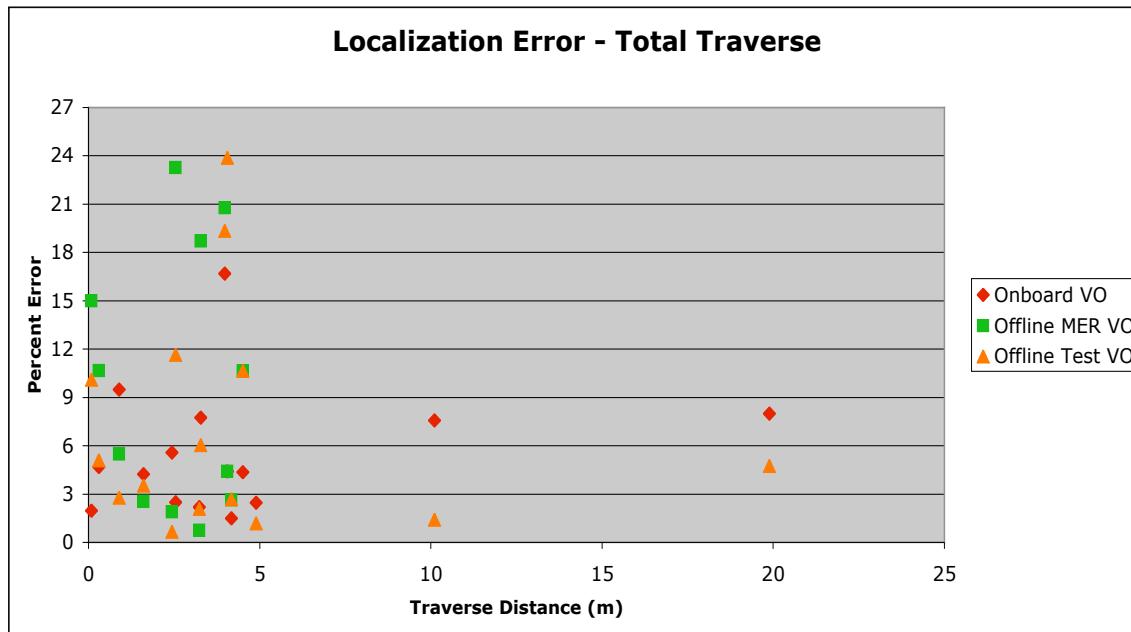


Chart 5. Scatterplot of VO localization error as a percent of the total distance traveled (from groundtruth measurements) versus the total distance traversed over all traverse runs.

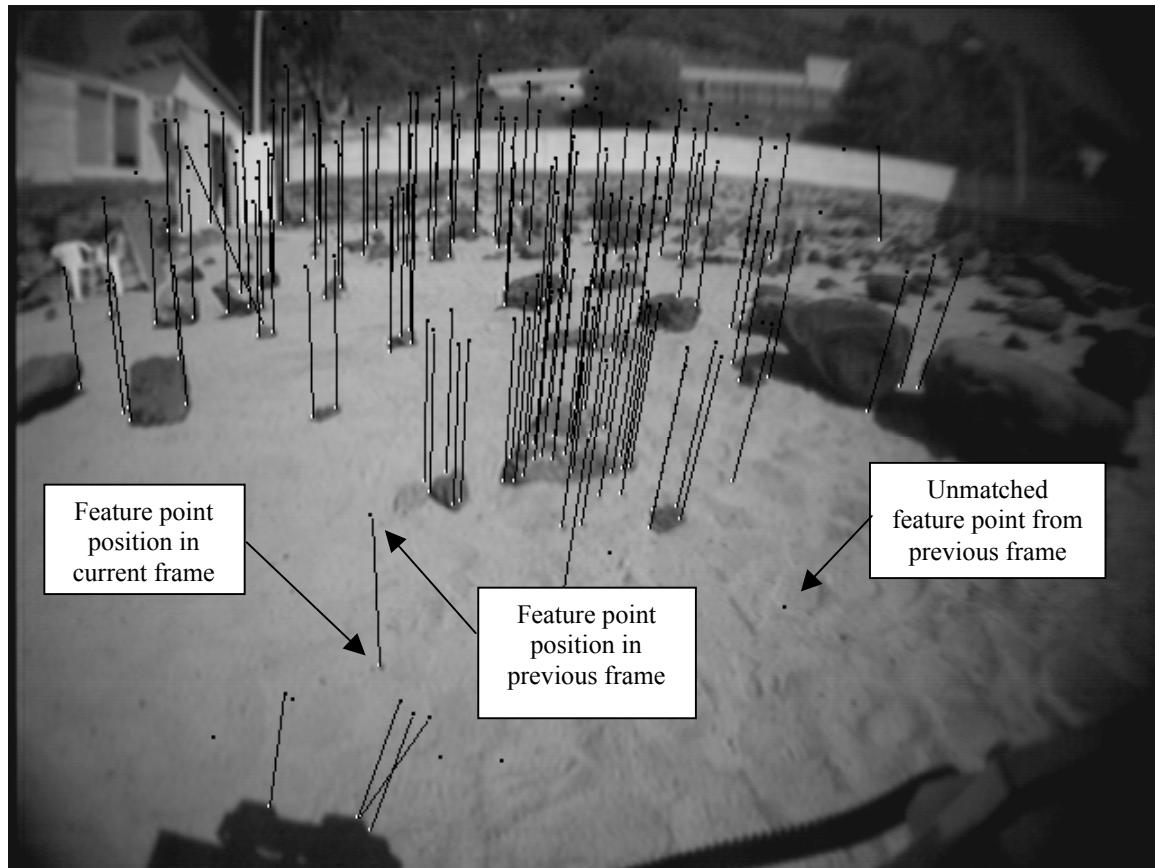
Detailed Test Results

Format for Test Results

Test results fall into two categories – those that are done in place (roll, pitch, height), and those that involve rover movement (yaw, and any of the traverses). The format for the summary table of results for each type of test is as follows (example shown below):

In Place:

Average Measured Value and RMS Error		Error compared to TotalStation ground truth
Measurement	Value	Error
GroundTruth	5.343°	
Onboard	5.107±0.058°	-0.236°
Offline MER	5.286±0.009°	-0.057°
Offline Test-Derived	5.075±0.001°	-0.268°



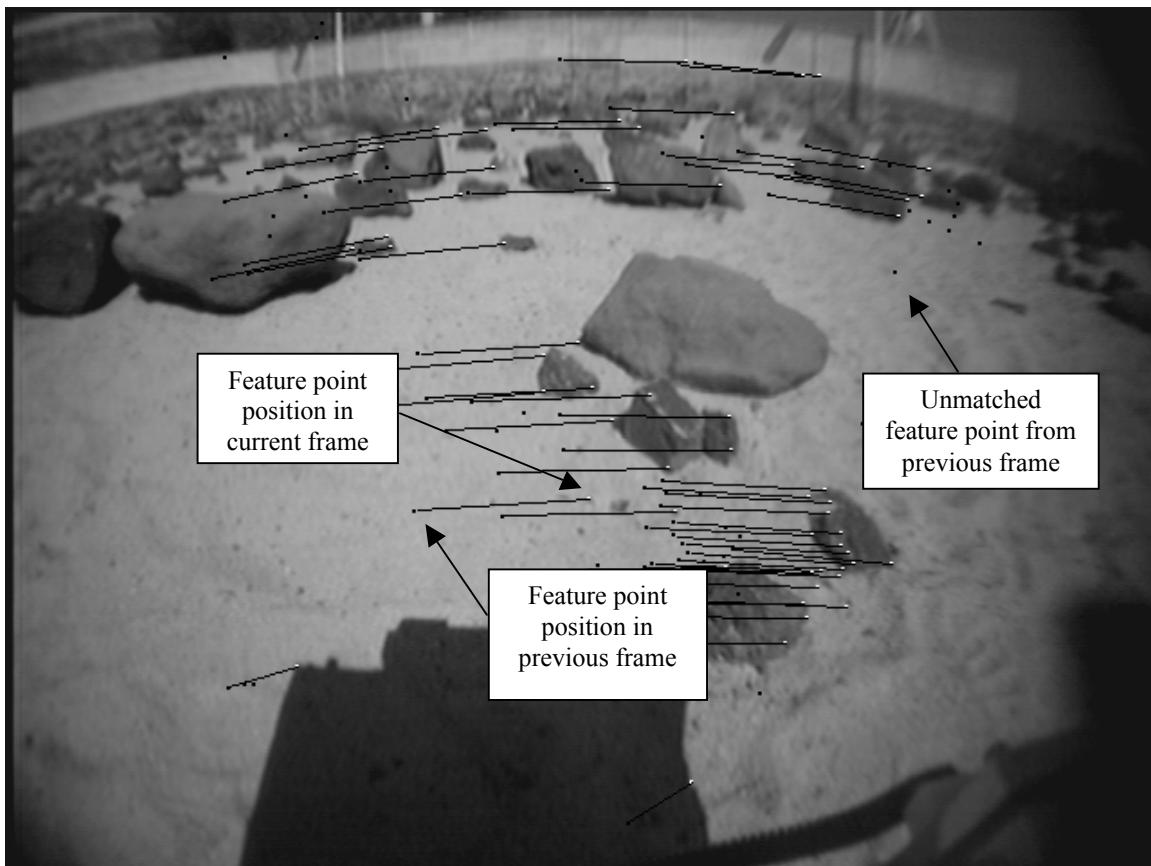
Sample composite vector overlay image based on two consecutive images taken during the test. The vectors connect the matched feature points (white dots are the positions of the feature points in the current image and black dots are the positions of the feature points in the previous image). Black dots that are isolated are feature points in the previous image that were not matched to any in the current image.

Notes:

1. The test results presented are the average values and rms variations from three runs.
2. In the event that any version of the algorithm fails to produce a value, the entries in the tables are annotated to indicate the failure mode.

Yaw:

Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
5.083°	5.0°	-0.083°	5.215°	0.132°	5.198°	0.115°
10.379°	10.212°	-0.167°	10.549°	0.170°	10.586°	0.207°
15.758°	15.621°	-0.137°	15.720°	-0.038°	15.903°	0.145°
21.128°	20.958°	-0.170°	20.837°	-0.291°	20.993°	-0.135°
5.282 ±0.060°	5.239 ±0.078°	-0.043° ±0.040°	5.209 ±0.040°	-0.073°	5.248 ±0.057°	-0.034°



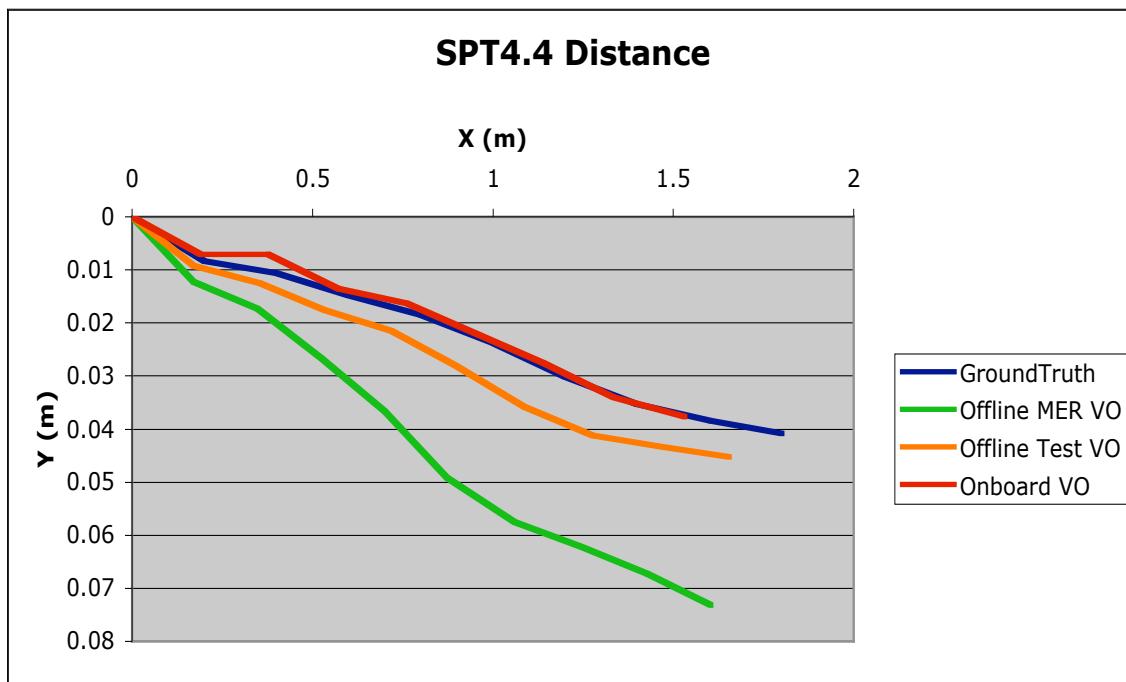
Sample composite vector overlay image based on two consecutive images taken during the test. The vectors connect the matched feature points (white dots are the positions of the feature points in the current image and black dots are the positions of the feature points in the previous image). Black dots that are isolated are feature points in the previous image that were not matched to any in the current image.

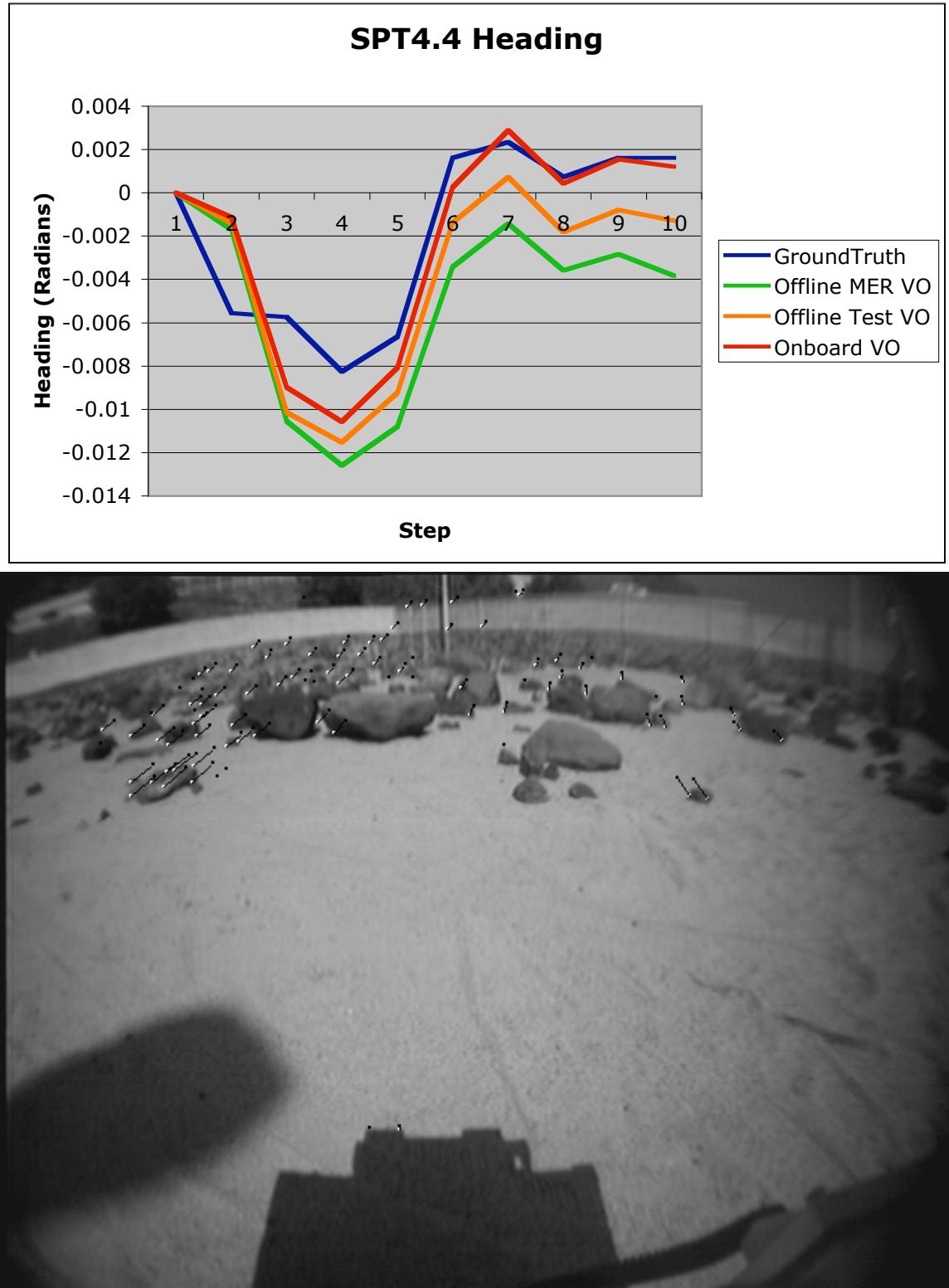
Notes:

1. The results presented in the first four rows are the cumulative values throughout the turn, and the last row gives results and errors for the average step size taken during the incremental turn.
2. In the event that any version of the algorithm fails to produce a value, the entries in the tables are annotated to indicate the failure mode.

Traverses:

	Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	1.601	1.532	-0.068	1.604	0.003	1.656	0.055
Y	0.032	0.037	0.005	0.073	0.041	0.045	0.013
Distance	1.602	1.532	4.24%	1.606	2.55%	1.657	2.77%
Heading	-0.093°	0.069°	0.162°	-0.220°	-0.127°	-0.074°	0.019°





Sample composite vector overlay image based on two consecutive images taken during the test. The vectors connect the matched feature points (white dots are the positions of the feature points in the current image and black dots are the positions of the feature points in the previous image). Black dots that are isolated are feature points in the previous image that were not matched to any in the current image.

Single Parameter Tests (SPT)

These tests were designed to test the system for the 6 DOF of the rover (X, Y, Z, roll, pitch, yaw) with a fixed set of VO parameters. There was no software control for motion along Y (lateral), so the Y DOF tests were not performed. All values reported for the Offline VO in the Tables for each test use MER default parameter settings from Table XX unless the algorithm failed, in which case the test-derived parameter settings from Table XY are used.

SPT1.1: Pitch of 5°

Measurement	Value	Error
GroundTruth	5.343°	
Onboard	5.107±0.058°	-0.236°
Offline MER	5.286±0.009°	-0.057°
Offline Test-Derived	5.075±0.001°	-0.268°



SPT1.2: Pitch of 10°

Measurement	Value	Error
GroundTruth	10.675°	
Onboard	†	
Offline MER	*	
Offline Test-Derived	10.515±0.002°	-0.16°

†Failed: singular matrix

*Failed: only 7 (min threshold of 8) features found.



SPT2.1: Roll of 5°

Measurement	Value	Error
GroundTruth	6.262°	
Onboard	6.081±0.010°	-0.181°
Offline MER	6.268±0.011°	0.006°
Offline Test-Derived	6.174±0.000°	-0.088°



SPT2.2: Roll of 10°

Measurement	Value	Error
GroundTruth	11.015°	
Onboard	10.879±0.016°	-0.136°
Offline MER	10.958±0.006°	-0.057°
Offline Test-Derived	10.913±0.001°	-0.102°



SPT2.3: Roll of 20°

Measurement	Value	Error
GroundTruth	22.485°	
Onboard	22.714±0.006°	0.229°
Offline MER	*	
Offline Test-Derived	22.693±0.004°	0.208°

*Failed: only 3 (min threshold of 8) features found.



SPT2.4: Roll of 30°

Measurement	Value	Error
GroundTruth	31.167°	
Onboard	†	
Offline MER	*	
Offline Test-Derived	33.095±0.004°	1.928°

†Failed: singular matrix

*Failed: only 3 (min threshold of 8) features.



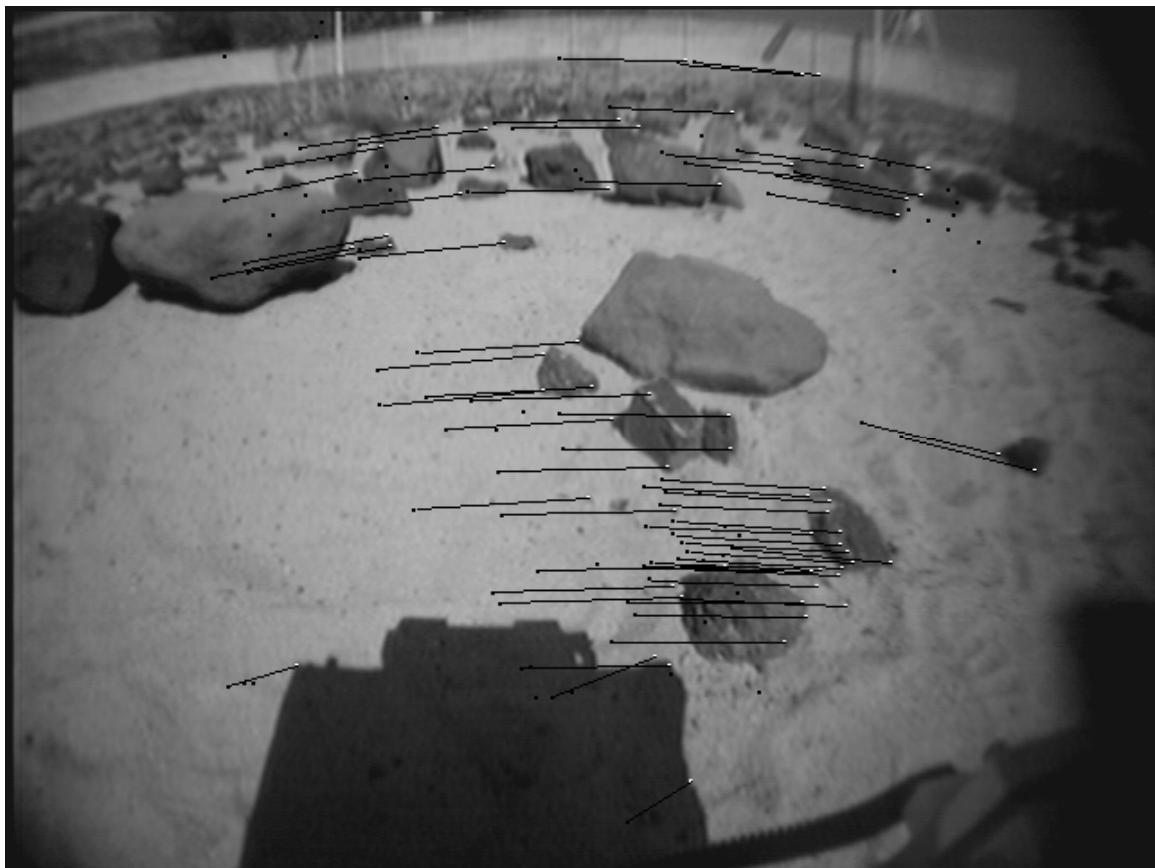
SPT3.1: Yaw in 5° steps

Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
5.083°	5.0°	-0.083°	5.215°	0.132°	5.198°	0.115°
10.379°	10.212°	-0.167°	10.549°	0.170°	10.586°	0.207°
15.758°	15.621°	-0.137°	15.720°	-0.038°	15.903°	0.145°
21.128°	20.958°	-0.170°	20.837°	-0.291°	20.993°	-0.135°
5.282 ±0.060°	5.239 ±0.078°	-0.043°	5.209 ±0.040°	-0.073°	5.248 ±0.057°	-0.034°



SPT3.2: Yaw in -10° steps

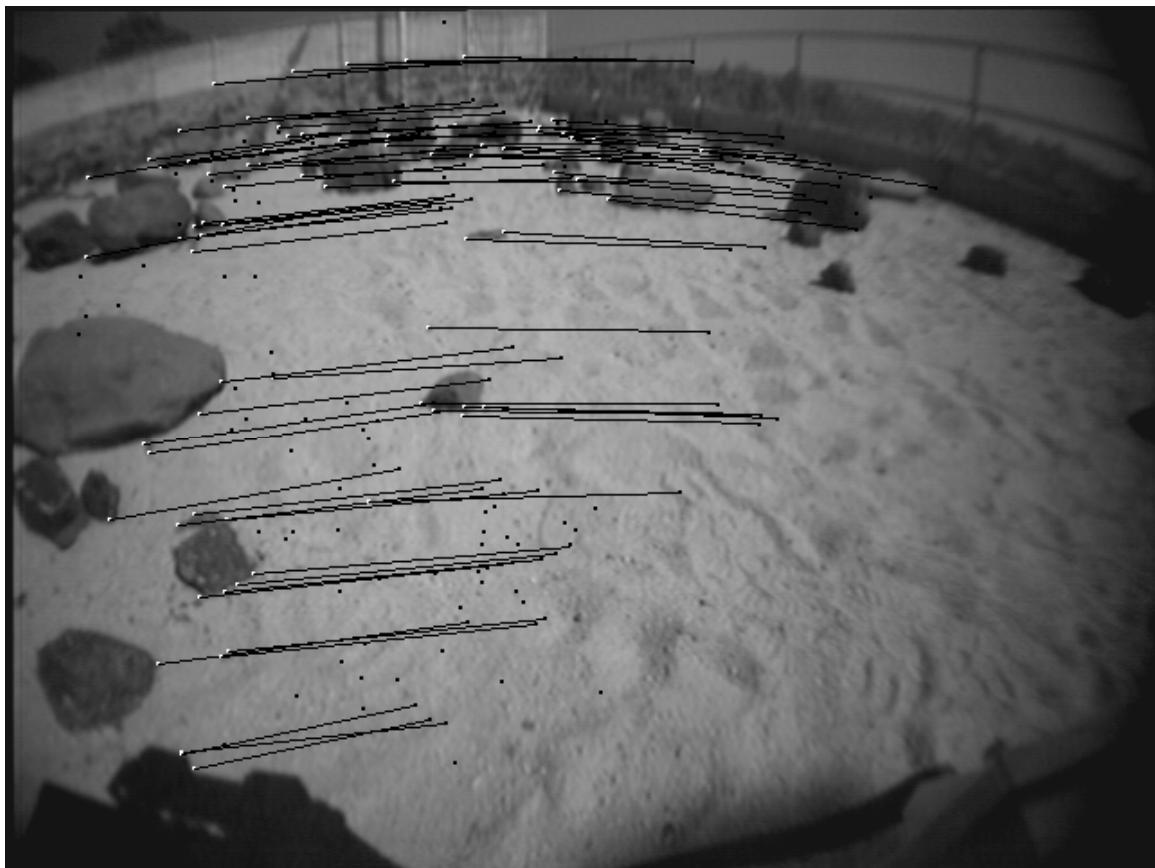
Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
-10.051°	-10.0°	0.051°	-9.766°	0.285°	-9.739°	0.115°
-20.754°	-19.736°	1.018°	-19.686°	1.068°	-19.612°	0.207°
-30.619°	-29.642°	0.977°	-30.146°	0.473°	-29.992°	0.145°
Bad Data	-40.099°		-40.053°		-39.817°	
-10.207 ±0.129°	-10.025 ±0.185°	0.182°	-10.013 ±0.132°	0.194°	-9.954 ±0.125°	0.253°



SPT3.3: Yaw in 20° steps

Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
Bad Data	20.0°		*	*	20.308°	
38.576°	40.316°	1.740°	*	*	40.322°	1.746°
59.048°	60.434°	1.386°	*	*	61.443°	1.395°
80.272°	81.646°	1.374°	79.376°	-0.926°	80.679°	0.407°
20.848 ±0.266°	20.411 ±0.238°	-0.437°	*	*	20.170 ±0.337°	-0.678°

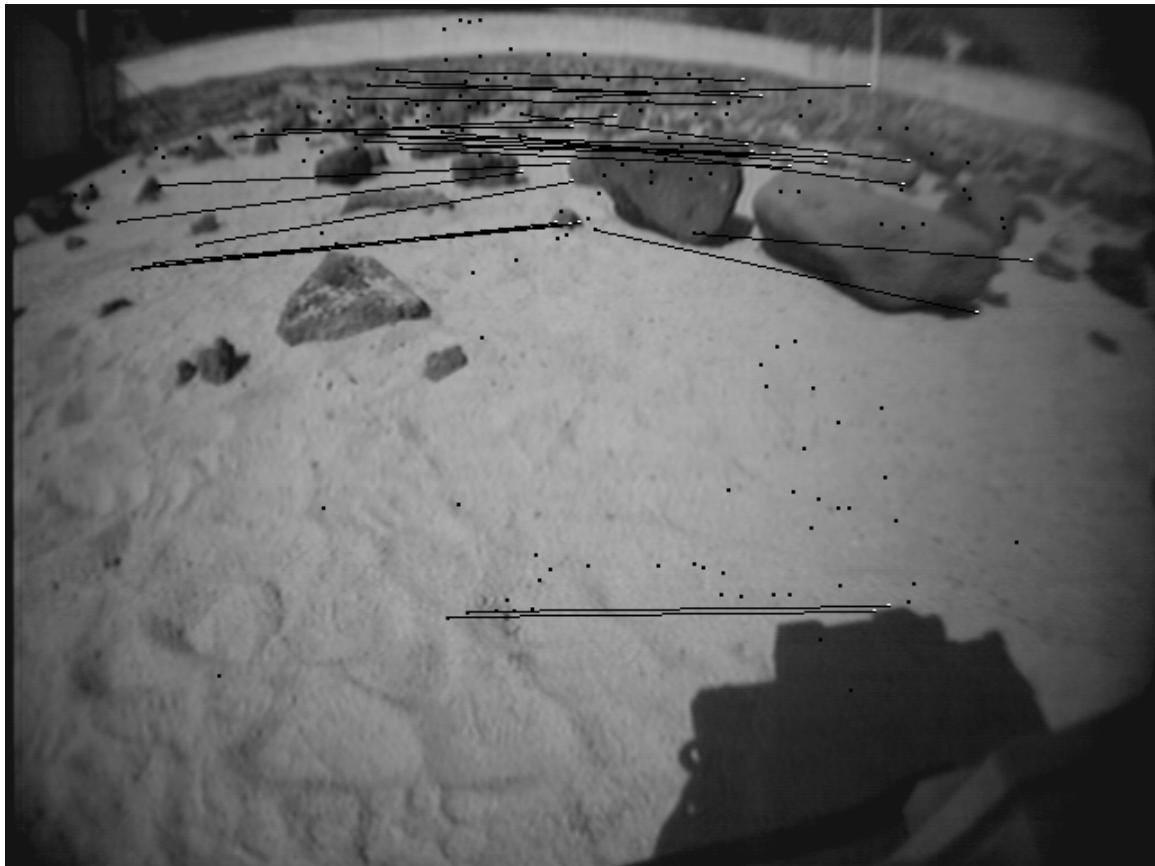
*Failed: Step 1 - too few features have small residuals in Schonemann outlier rejection; Step 2 – algorithm didn't converge in 50 iterations; Step 3 – only 7 (min threshold of 8) features found; Step 4 – successful with yaw of 79.376° and error of -0.896°.



SPT3.4: Yaw in -30° steps

Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
-30.712°	-30.0°	0.712°	*	*	-31.373°	-0.661°
-62.312°	-63.176°	-0.864°	*	*	-60.413°	1.899°
Bad Data	-93.443°		*	*	-90.900°	
-123.655°	-122.917°	0.738°	*	*	-121.625°	2.030°
-31.019 $\pm 0.237^\circ$	-30.729	-0.610°	*	*	-30.406 $\pm 0.426^\circ$	-0.387°

*Failed: Step 1 – only 3 (min threshold of 8) features found; Step 2 - only 7 (min threshold of 8) features found; Step 3 - only 7 (min threshold of 8) features found; Step 4 - no (min threshold of 8) features found.



SPT3.5: Yaw in -45° steps

Ground Truth	Onboard †	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
-45.084°	-45.0°	0.084°	*	*	¢	¢
-91.494°	-90.0°	1.494°	*	*	¢	¢
-136.540°	-137.3°	-0.760°	*	*	¢	¢
-184.434°	-182.3°	2.134°	*	*	¢	¢
-46.109 ±0.584°	-45.575 ±0.498°	0.634°	*	*	¢	¢

†Failed: Step 2 – singular matrix and too few features have small residuals in Schonemann outlier rejection; Step 3 – singular matrix; Step 4 - singular matrix and too few features have small residuals in Schonemann outlier rejection.

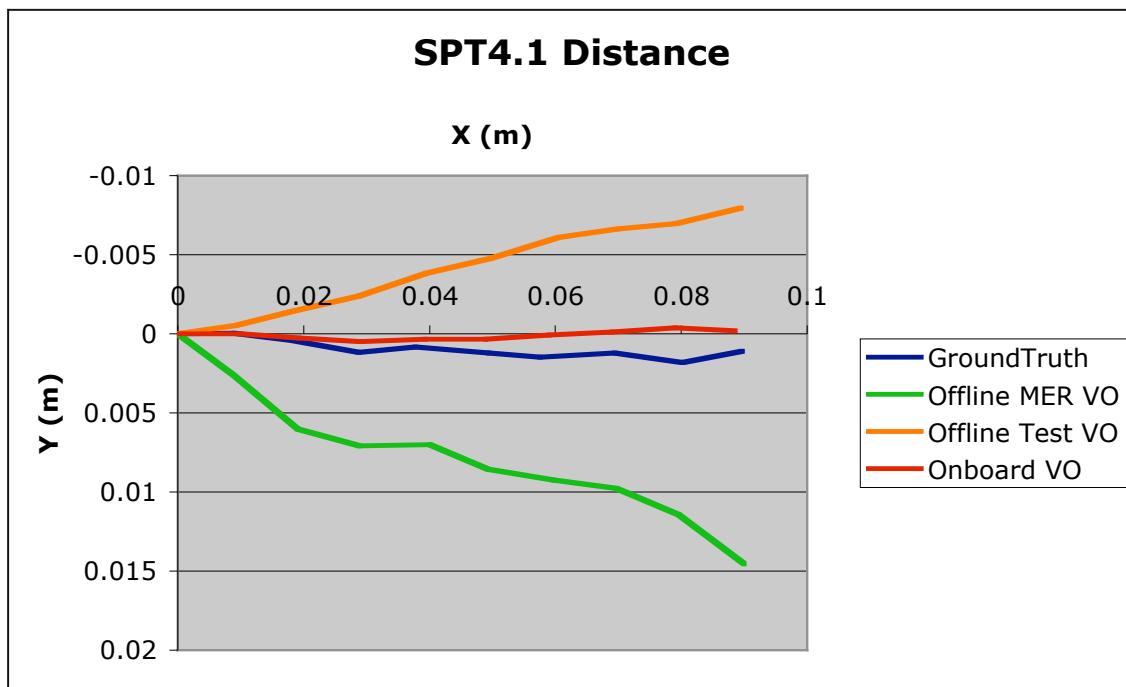
*Failed: Step 1 - only 2 (min threshold of 8) features found; Step 2 – only 4 (min threshold of 8) features found; Step 3 – no (min threshold of 8) features found.

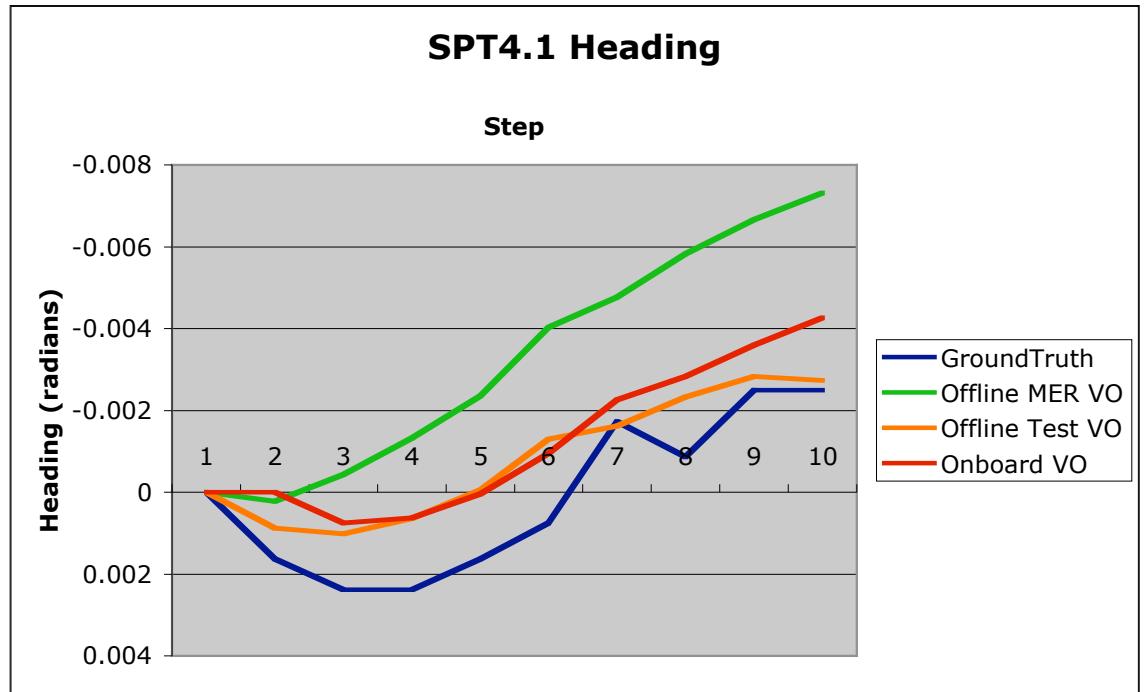
¢Failed: Step 1 - only 7 (min threshold of 8) features found; Step 2 – only 7 (min threshold of 8) features found; Step 3 – only 7 (min threshold of 8) features found.



SPT4.1: Drive 0.1 m in X in 0.01 m steps

	Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	0.090	0.089	-0.001	0.090	0.000	0.090	0.000
Y	0.001	0.000	-0.001	0.015	0.014	-0.008	-0.009
Distance	0.090	0.089	1.96%	0.091	14.99%	0.090	10.08%
Heading	-0.143°	-0.250°	-0.107°	-0.419°	-0.276°	-0.156°	-0.013°



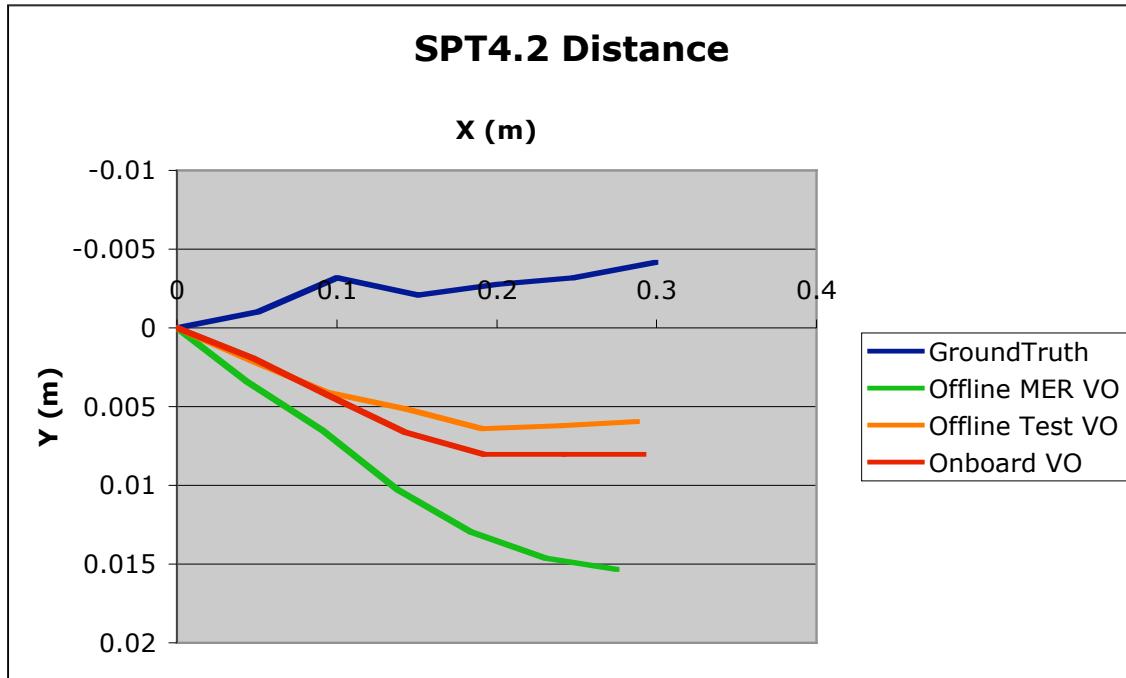


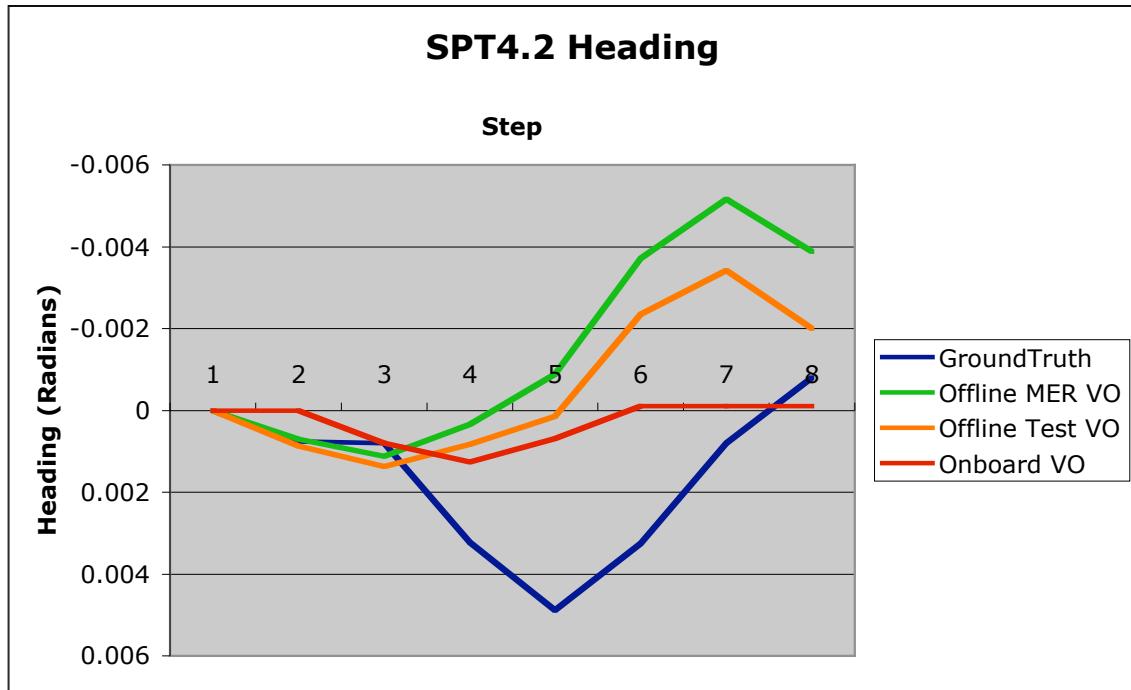
SPT4.2: Drive 0.5 m in X in 0.05m steps

	Ground Truth*	Onboard †	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	0.299	0.292	-0.007	0.275	-0.024	0.288	-0.011
Y	-0.006	0.008	0.014	0.015	0.021	0.006	-0.012
Distance	0.299	0.292	4.68%	0.276	10.67%	0.288	5.07%
Heading	-0.046°	-0.006°	0.052°	-0.222°	-0.176°	-0.114°	-0.068°

*Bad data after Step 7.

†Singular matrix on Step 6.

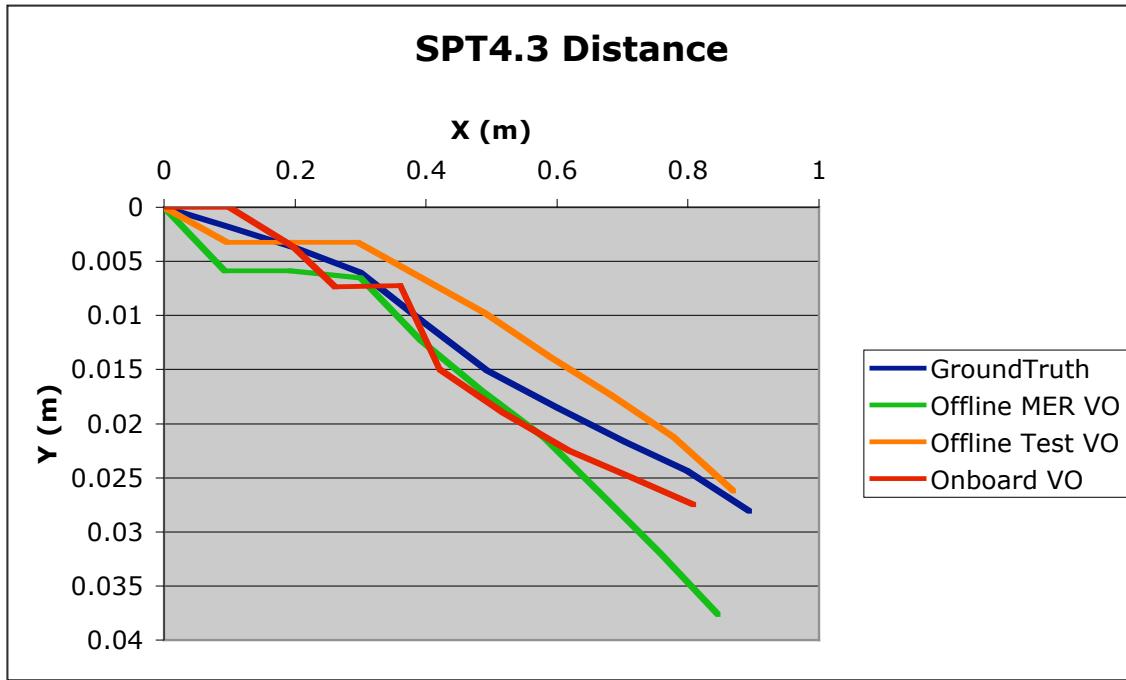


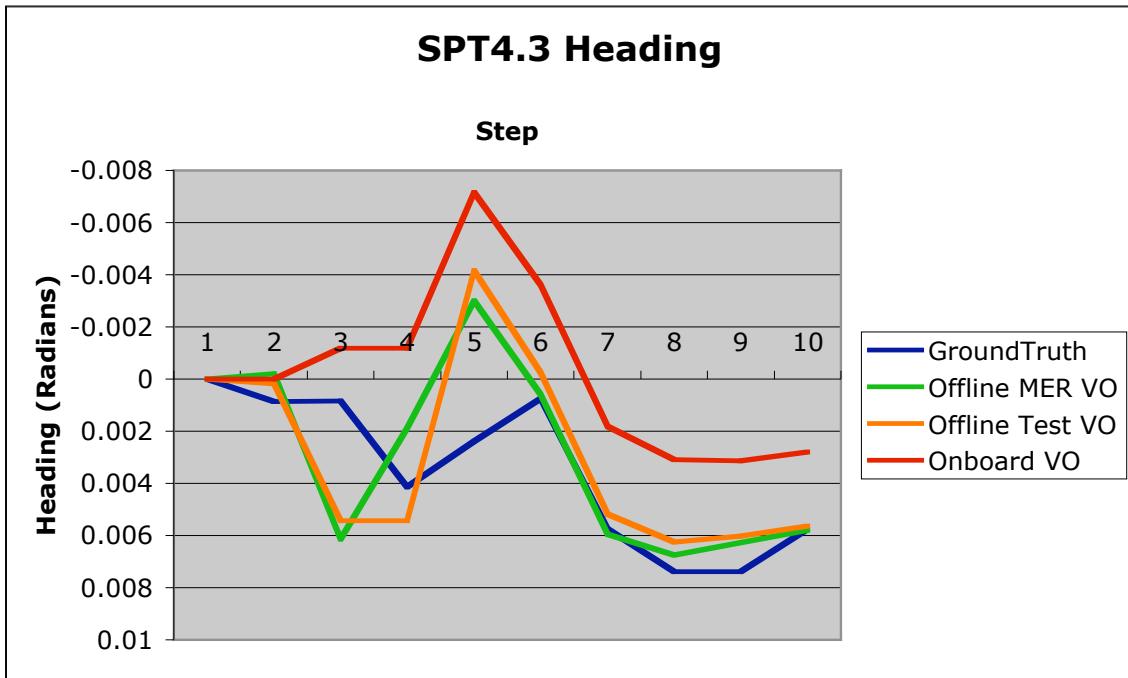


SPT4.3: Drive 1.0 m in X in 0.1m steps

	Ground Truth	Onboard *	Onboard Error	Offline MER*	Offline MER Error	Offline Test-Derived*	Offline Test-Derived Error
X	0.894	0.809	-0.085	0.846	-0.048	0.869	-0.025
Y	0.028	0.027	0.001	0.038	0.010	0.026	-0.002
Distance	0.895	0.809	9.50%	0.847	5.48%	0.870	2.77%
Heading	0.330°	0.180°	-0.150°	0.332°	0.002°	0.328°	-0.002°

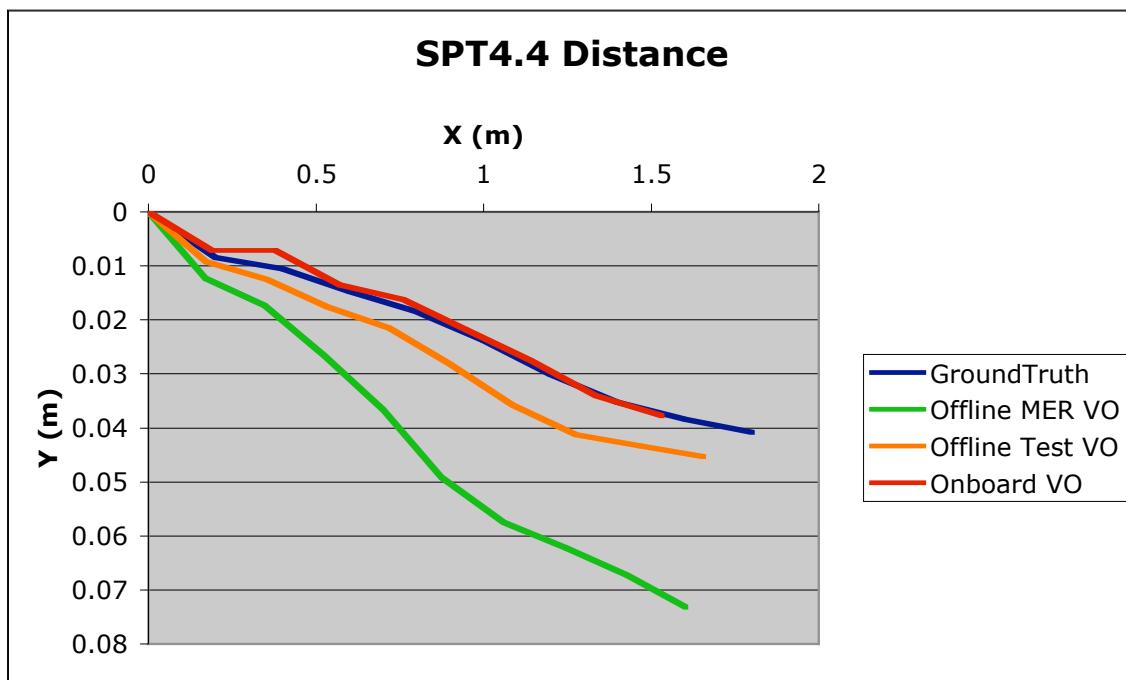
*Bad image on Step 2.

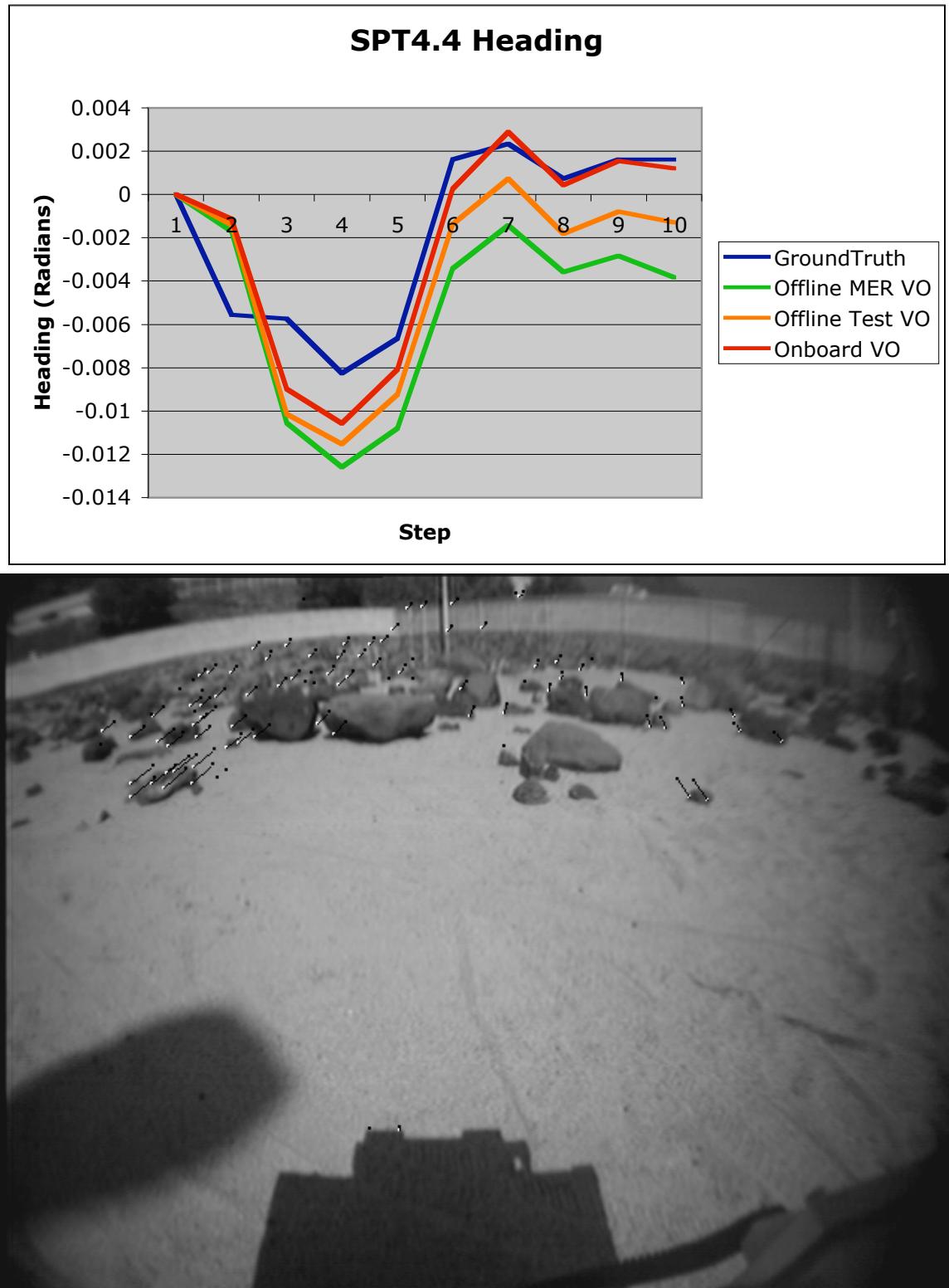




SPT4.4: Drive 1.6 m in X in 0.2m steps

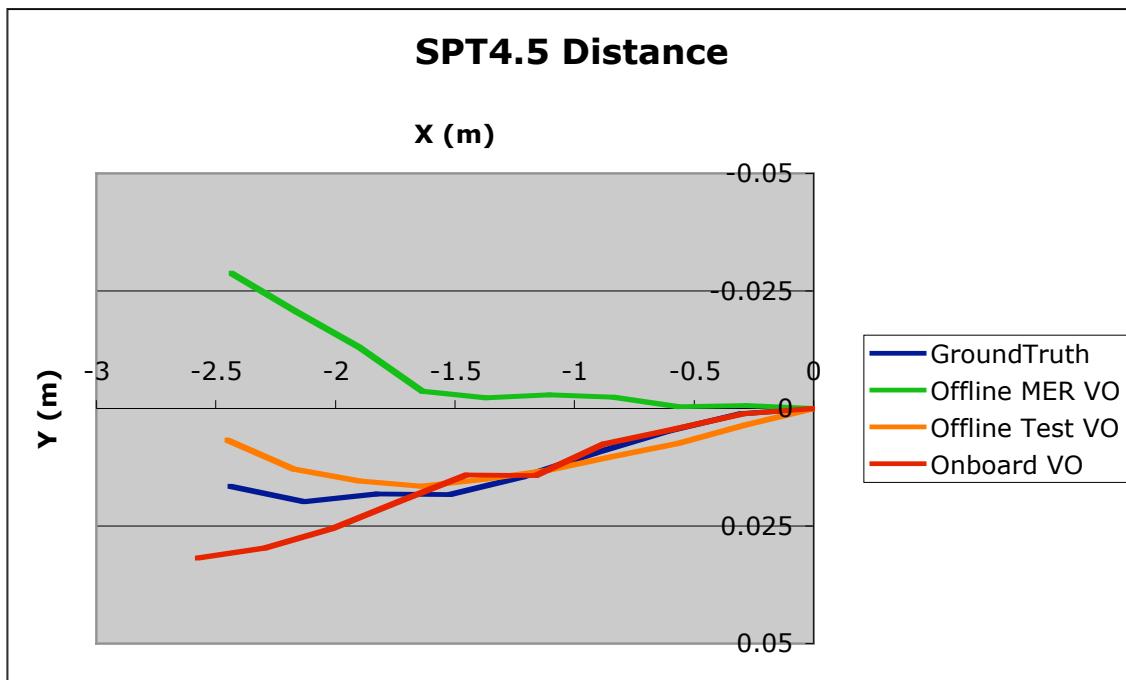
	Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	1.601	1.532	-0.068	1.604	0.003	1.656	0.055
Y	0.032	0.037	0.005	0.073	0.041	0.045	0.013
Distance	1.602	1.532	4.24%	1.606	2.55%	1.657	2.77%
Heading	-0.093°	0.069°	0.162°	-0.220°	-0.127°	-0.074°	0.019°

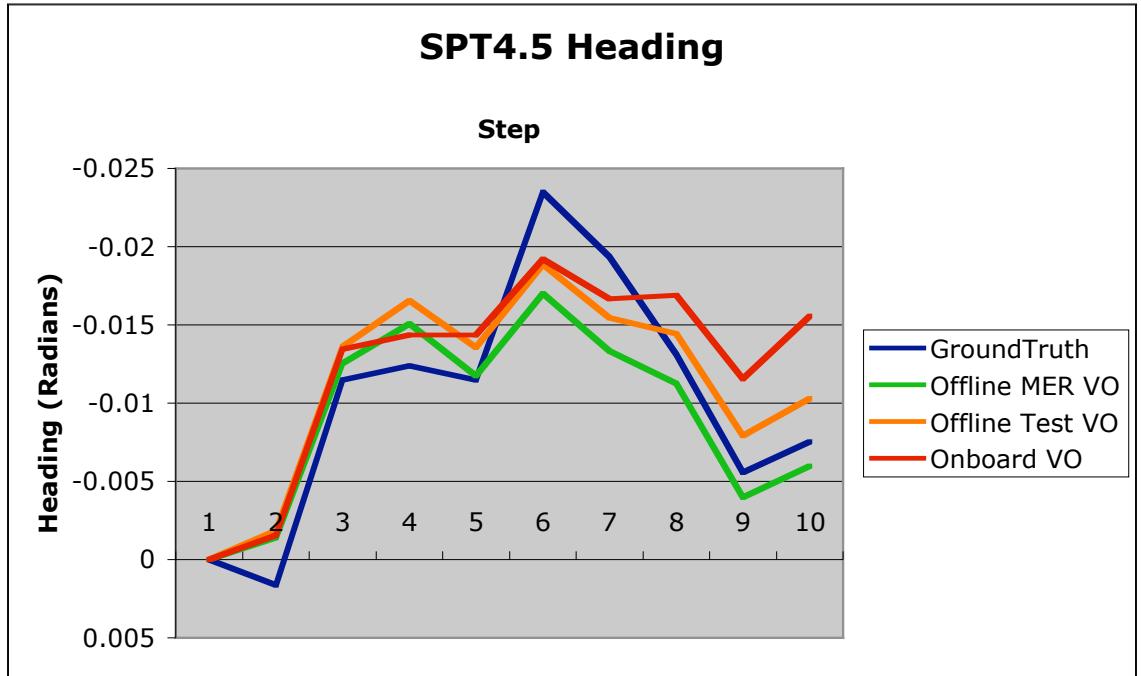




SPT4.5: Drive -3m in X in 0.3m steps

	Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	-2.441	-2.577	-0.136	-2.436	0.005	-2.453	-0.012
Y	0.017	0.032	0.015	-0.029	-0.046	0.006	-0.011
Distance	2.441	2.577	5.57%	2.436	1.90%	2.454	0.64%
Heading	-0.443°	-0.892°	-0.449°	-0.343°	0.100°	-0.590°	-0.147°

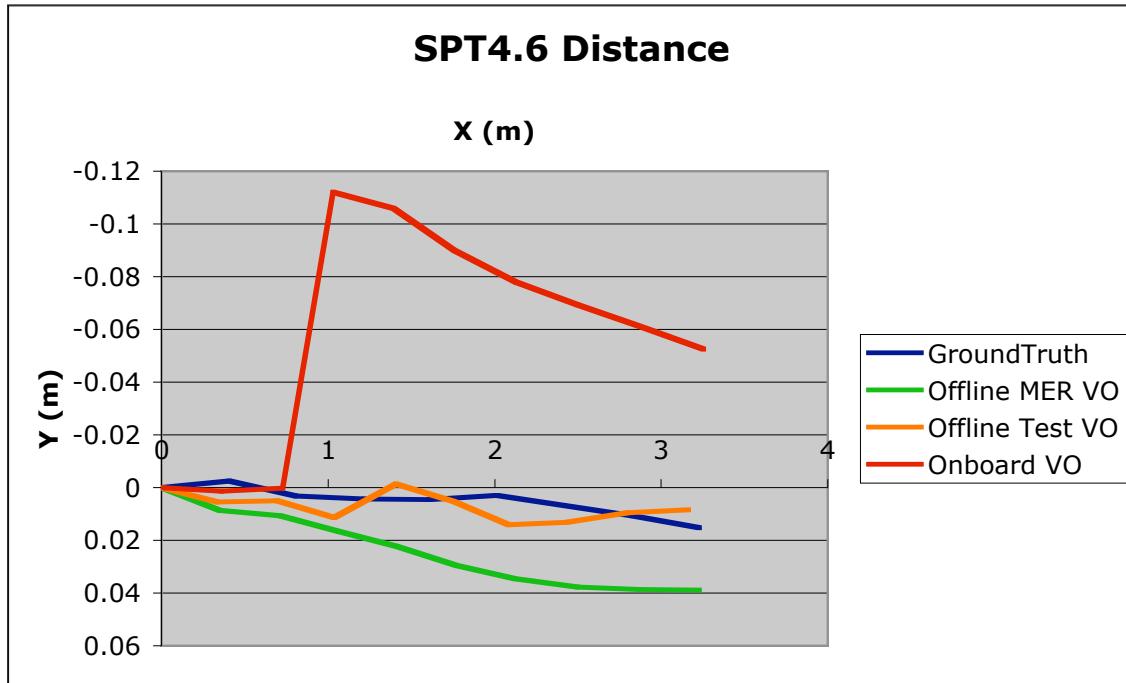


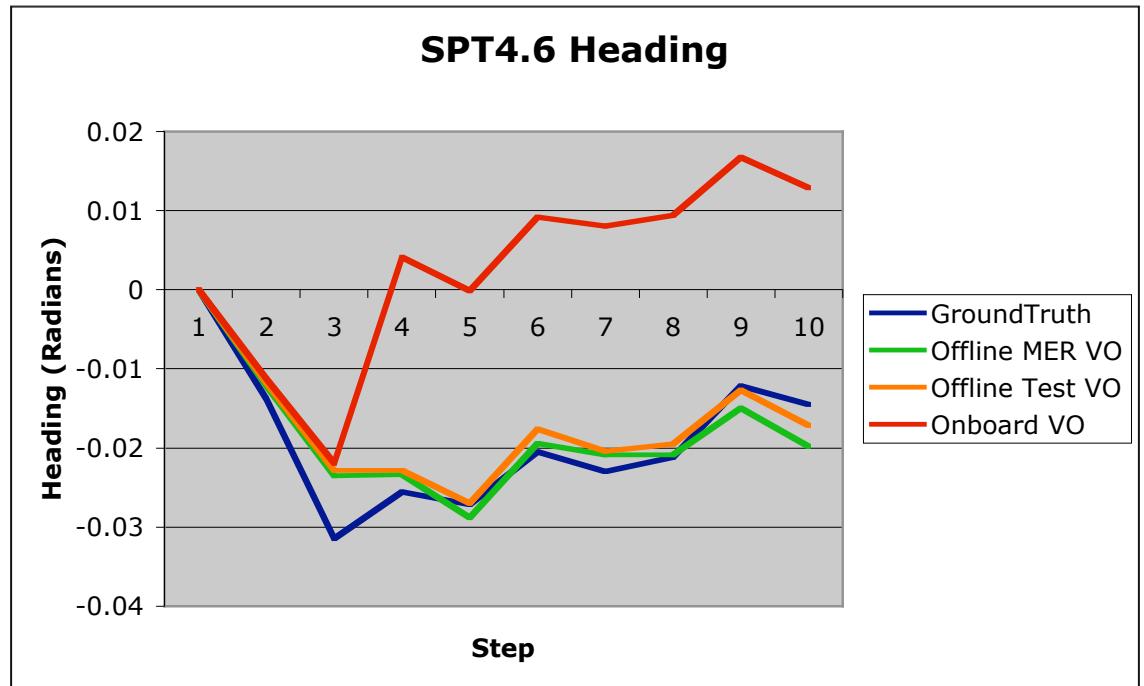


SPT4.6: Drive 3.2 m in X in 0.4 m steps

	Ground Truth	Onboard *	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	3.231	3.254	0.023	3.230	-0.001	3.164	-0.067
Y	0.015	-0.052	-0.067	0.039	0.024	0.008	-0.007
Distance	3.231	3.254	2.19%	3.231	0.74%	3.164	2.06%
Heading	-0.83°	0.92°	1.75°	-1.14°	-0.31°	-0.981°	-0.151°

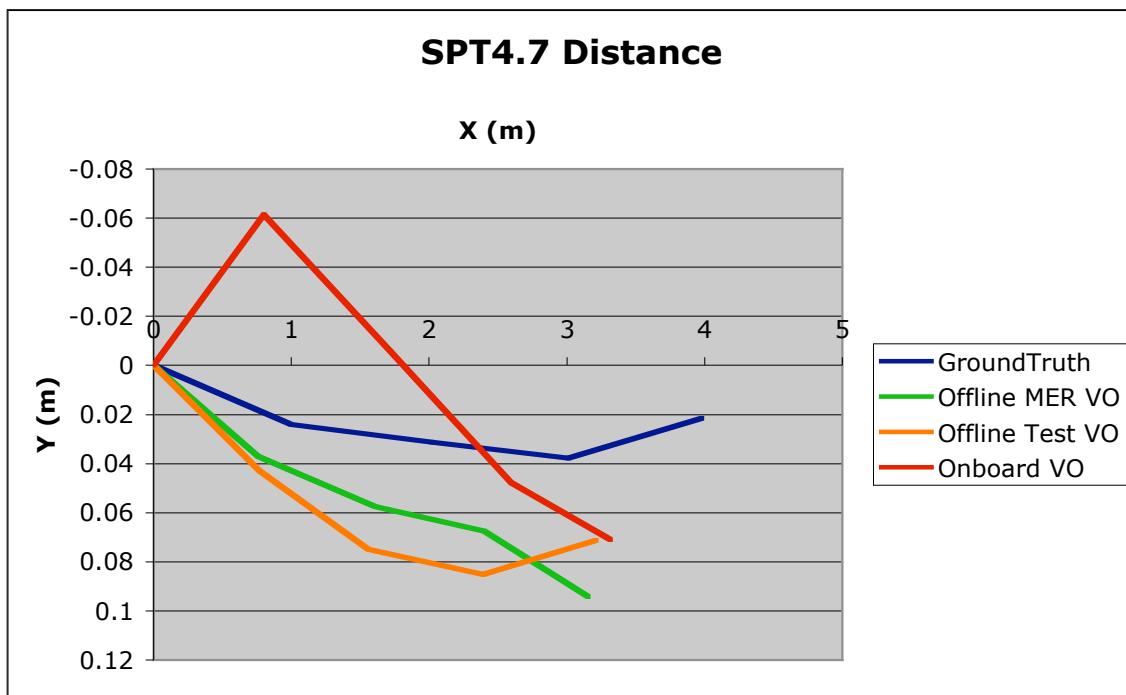
*Error in wheel odometry seed to algorithm for Step 3.

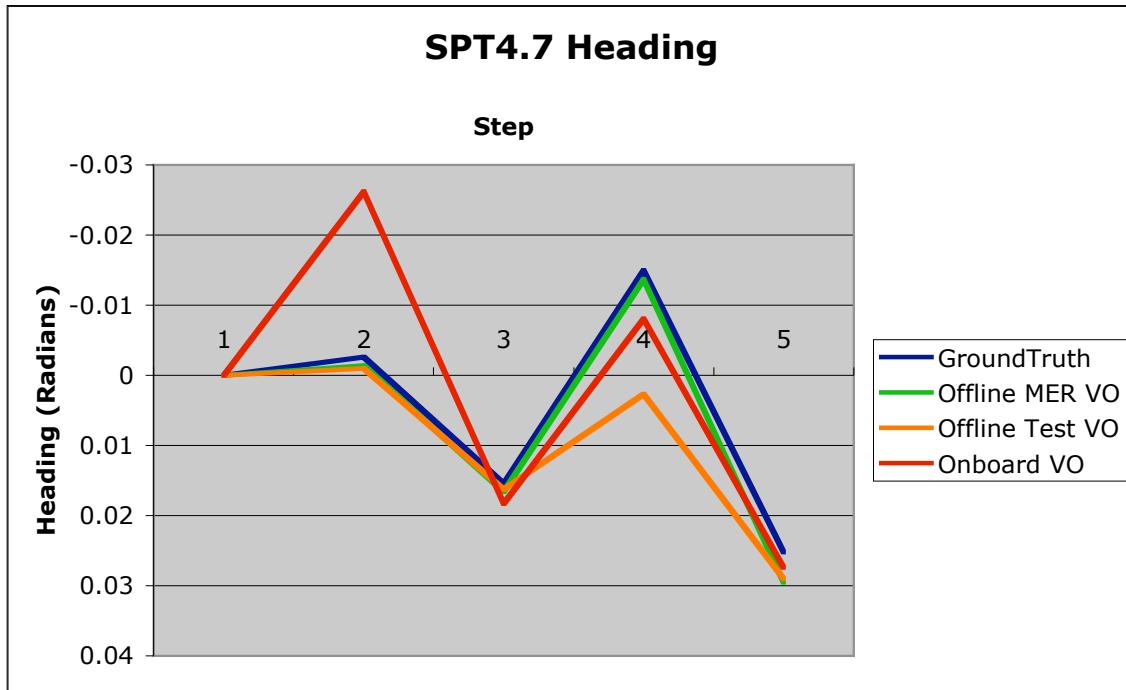




SPT4.7: Drive 4 m in X in 1.0 m steps

	Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	3.982	3.317	-0.665	3.153	-0.829	3.214	-0.768
Y	0.021	0.071	0.050	0.094	0.073	0.071	0.050
Distance	3.982	3.318	16.68%	3.155	20.77%	3.164	19.32%
Heading	1.44°	1.57°	0.13°	1.69°	0.25°	1.15°	-0.29°



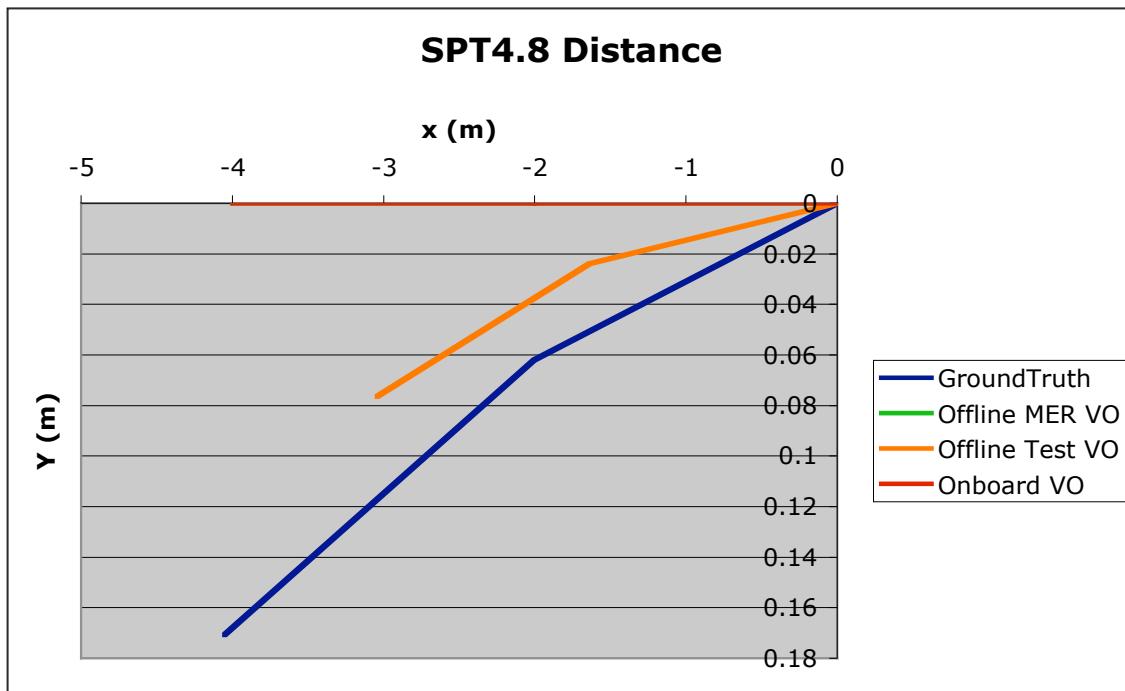


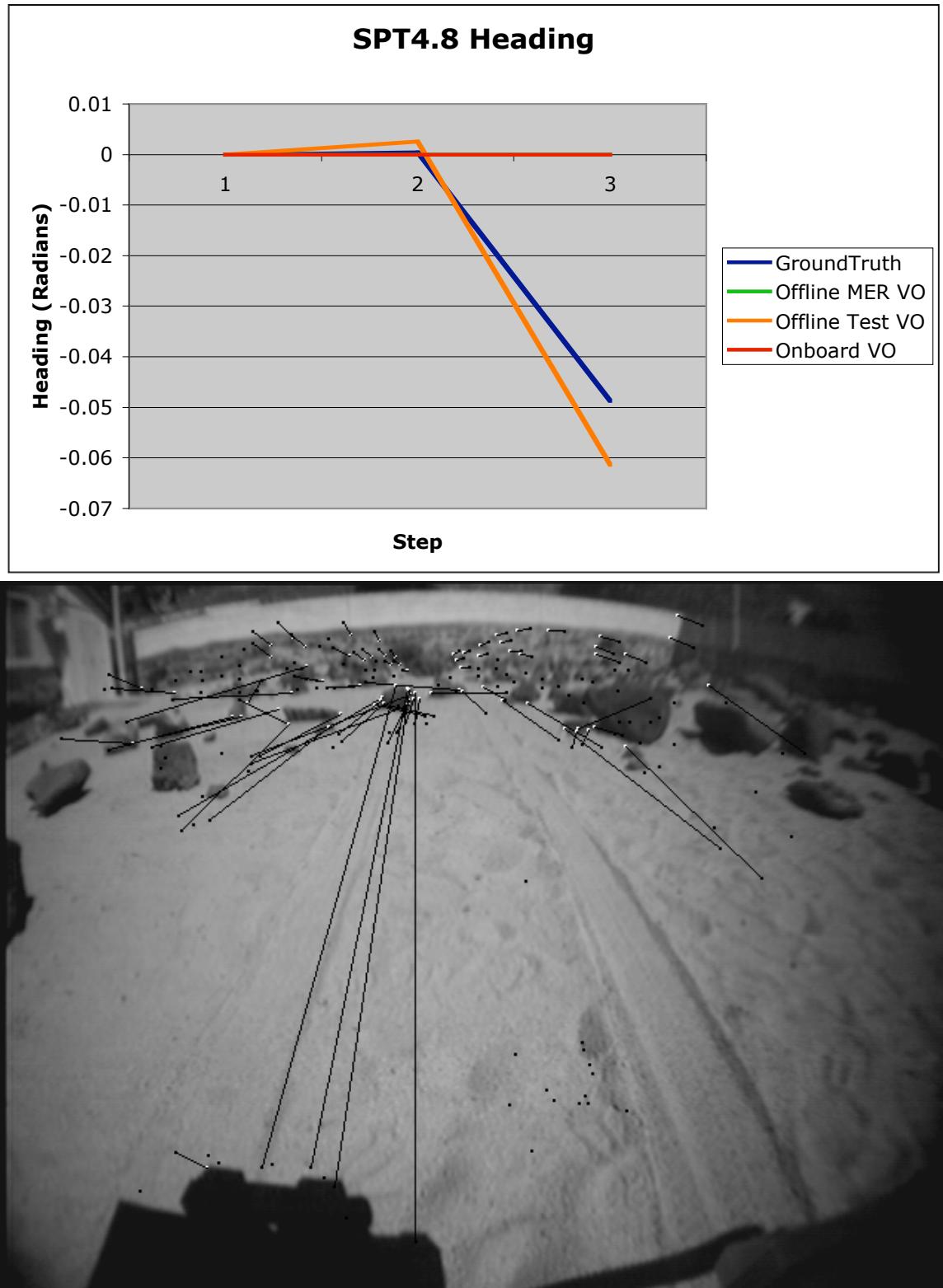
SPT4.8: Drive -4 m in X in 2.0 m steps

	Ground Truth	Onboard *	Onboard Error	Offline MER†	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	-4.052	-4.000	0.052	-4.000	0.052	-3.079	-0.973
Y	0.171	0.000	-0.171	0.000	-0.171	0.239	0.068
Distance	4.055	4.000	4.41%	4.000	4.41%	3.088	23.85%
Heading	-2.79°	0.00°	2.79°	0.00°	2.79°	-3.51°	-0.72°

*Wheel odometry only due to singular matrix in Step 1 and too few features have small residuals in Schonemann outlier rejection for Step 2.

†Failed: Too few features have small residuals in Schonemann outlier rejection for Steps 1 and 2.



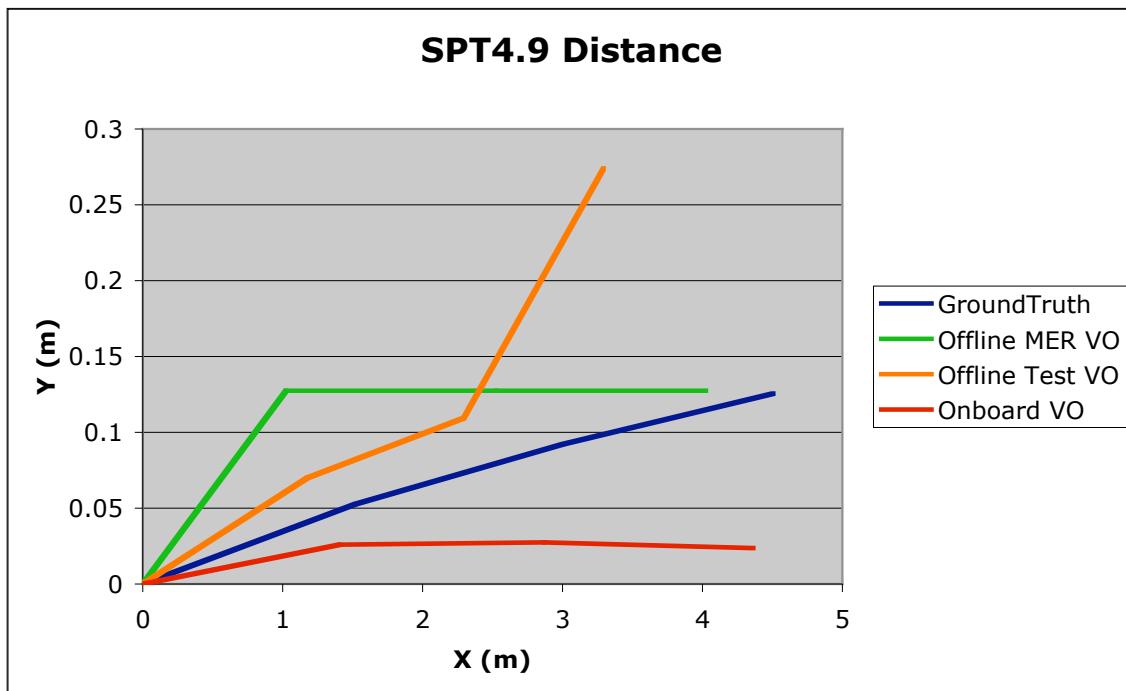


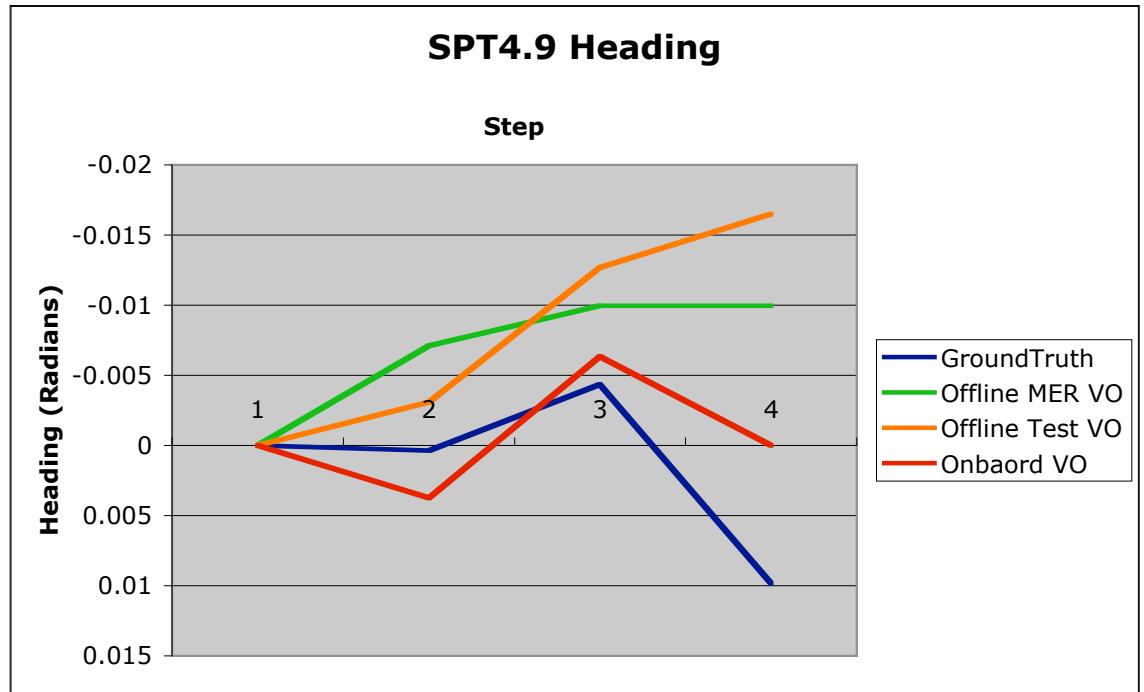
SPT4.9: Drive 4.5 m in X in 1.5 m steps

	Ground Truth	Onboard *	Onboard Error	Offline MER†	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	4.505	4.364	0.052	4.026	-0.479	3.293	-1.212
Y	0.126	0.024	-0.102	0.127	0.001	0.274	0.148
Distance	4.507	4.364	2.54%	4.028	10.63%	3.305	27.09%
Heading	0.56°	0.00°	-0.56°	-0.57°	-1.13°	-0.95°	-1.51°

*Failed: Singular matrix and too few features have small residuals in Schonemann outlier rejection for Step 3.

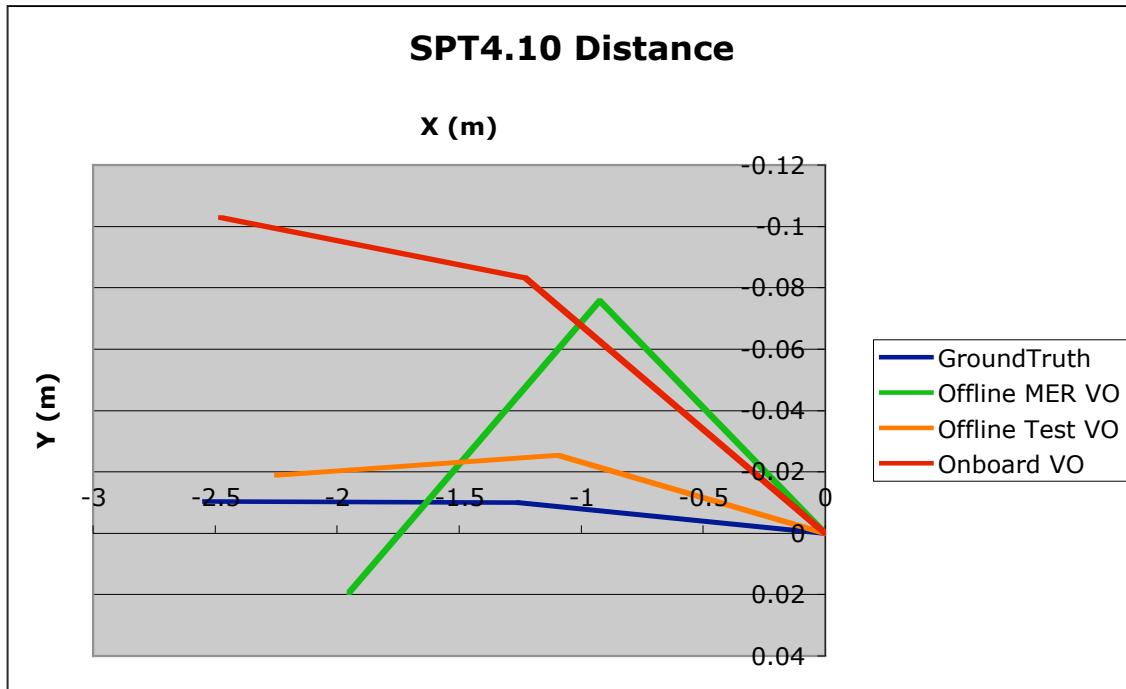
†Failed: Too few features have small residuals in Schonemann outlier rejection for Steps 2 and 3.

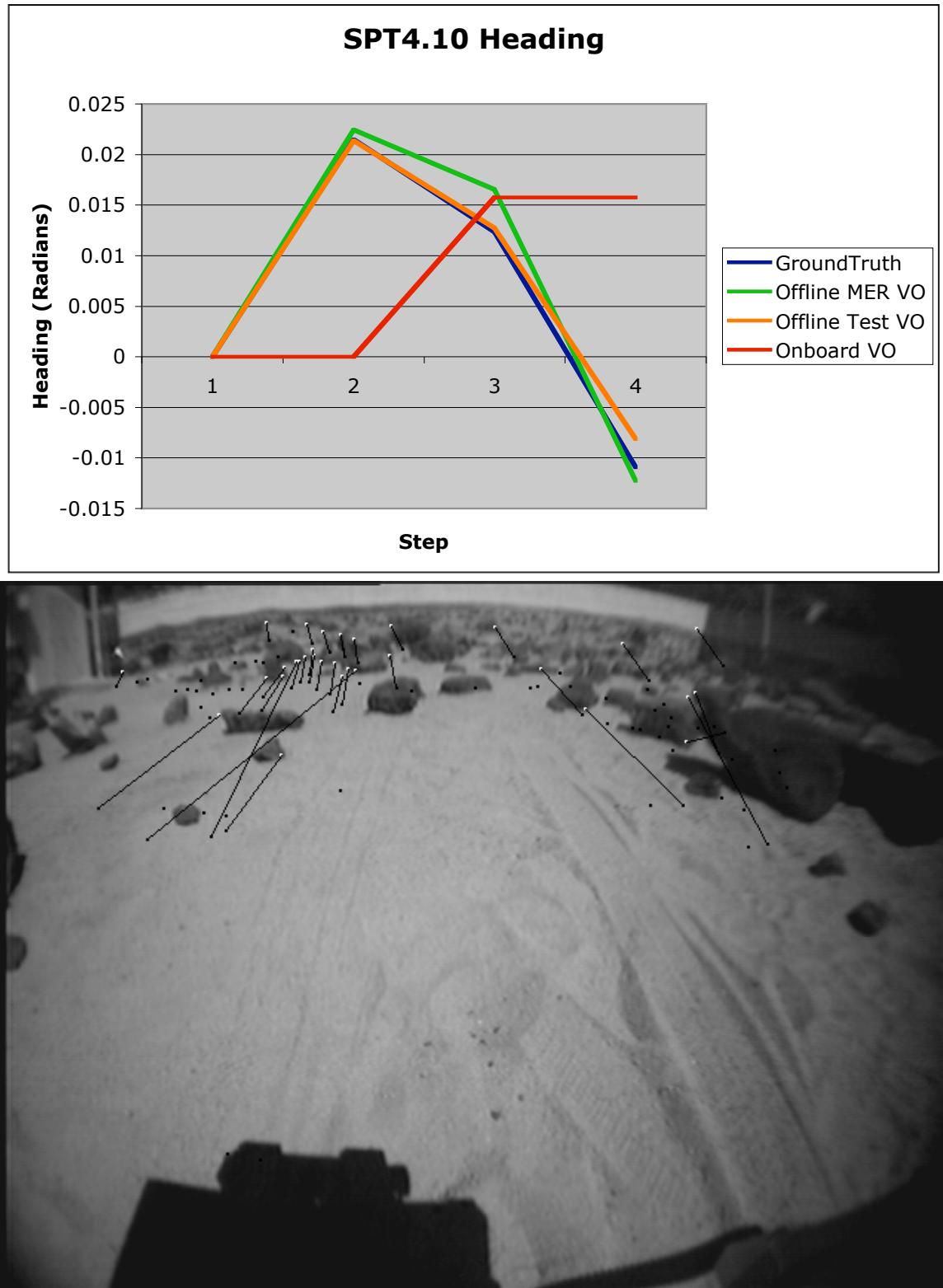




SPT4.10: Drive -2.50 m in X in 1.25 m steps

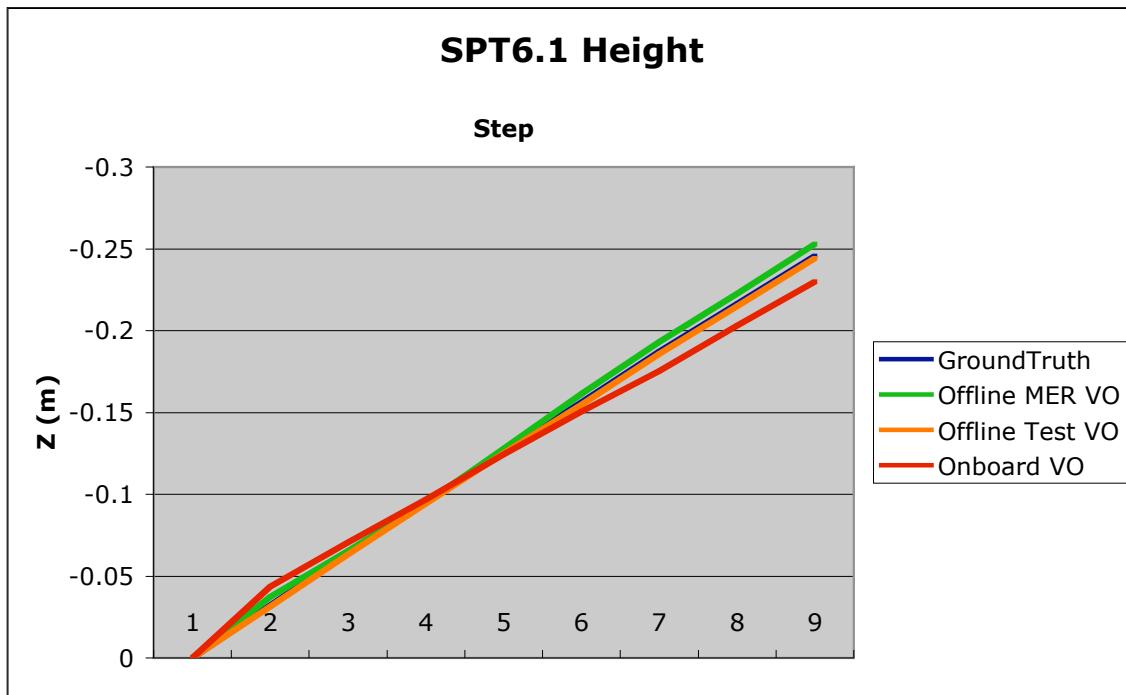
	Ground Truth	Onboard *	Onboard Error	Offline MER†	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	-2.544	-2.479	0.065	-1.952	0.592m	-2.248	0.296
Y	-0.010	-0.103	-0.093	0.019	0.029m	-0.019	-0.009
Distance	2.544	2.481	2.48%	1.952	23.27%	2.248	11.63%
Heading	-0.63°	0.90°	1.53°	-0.70°	-0.07°	-1.69°	-1.03°





SPT6.1: Lift 0.27 m in 0.03 m steps

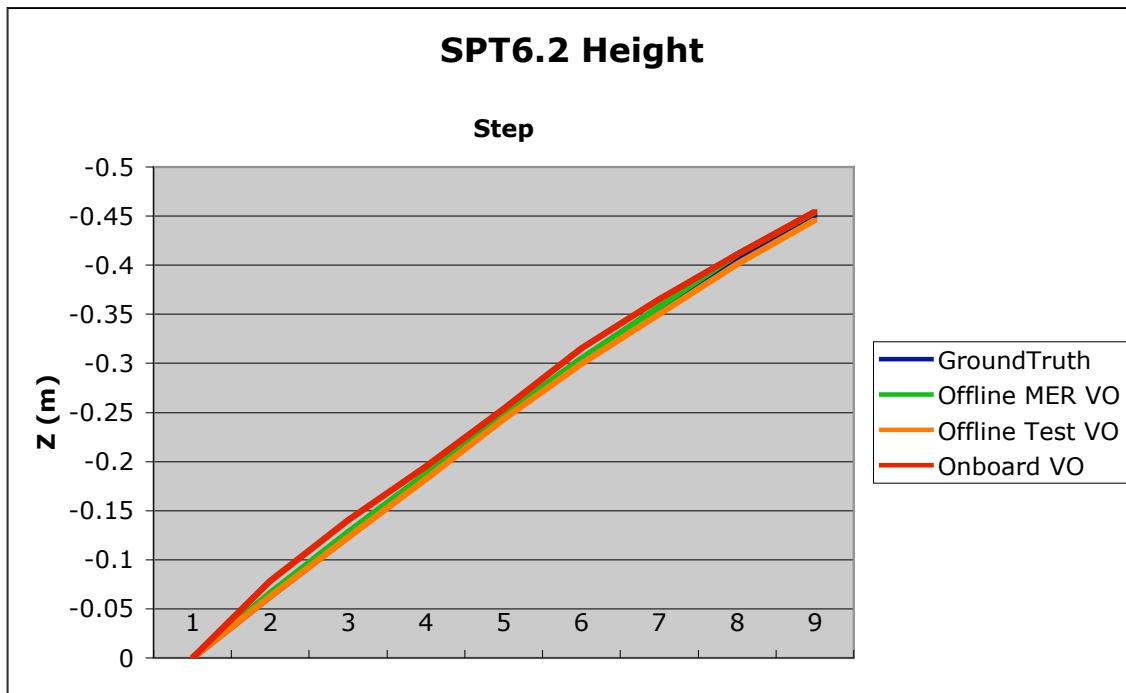
Measurement	Value	Error
GroundTruth	-0.246m	
Onboard	-0.256m	-0.010m
Offline MER	-0.253m	-0.007m
Offline Test-Derived	-0.244m	-0.002m





SPT6.2: Lift 0.54 m in 0.06 m steps

Measurement	Value	Error
GroundTruth	-0.451m	
Onboard	-0.455m	-0.004m
Offline MER	-0.454m	-0.003m
Offline Test-Derived	-0.446m	-0.005m



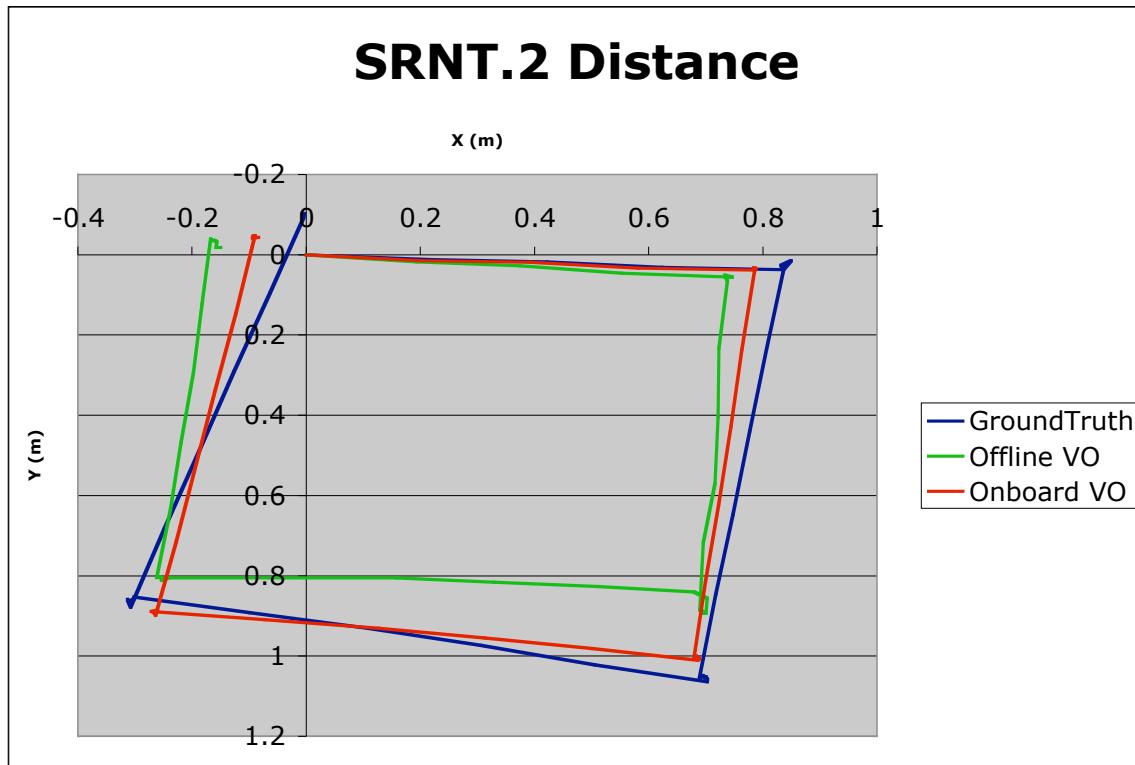


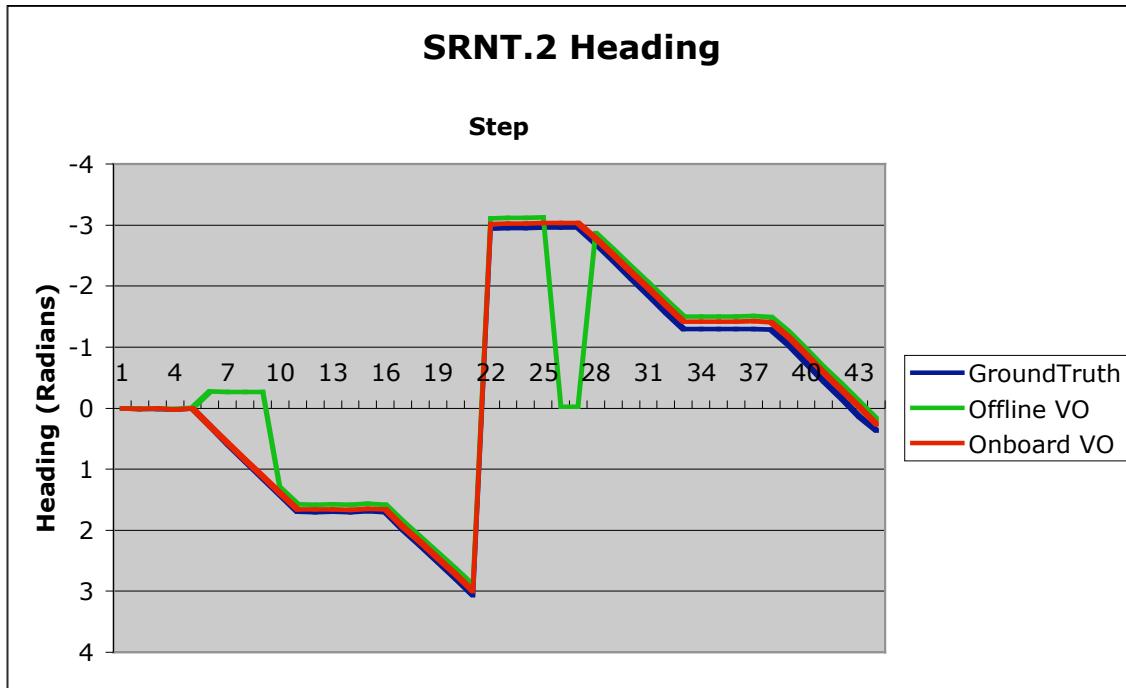
Short Range Navigation Tests (SRNT)

This series was designed to test the performance of the VO algorithm for short range traverses with heading changes.

SRNT.2: Square Drive – 1 m on a side

	Ground Truth	Onboard VO	Onboard Error	Offline VO	Offline Error
X	-0.082m	-0.084m	-0.002m	-0.150m	-0.068m
Y	-0.106m	-0.044m	0.062m	-0.018m	0.088m
Distance	4.172m	3.774m	1.49%	3.529m	2.67%
Heading	21.201°	15.430°	-5.771°	10.210°	-10.991°

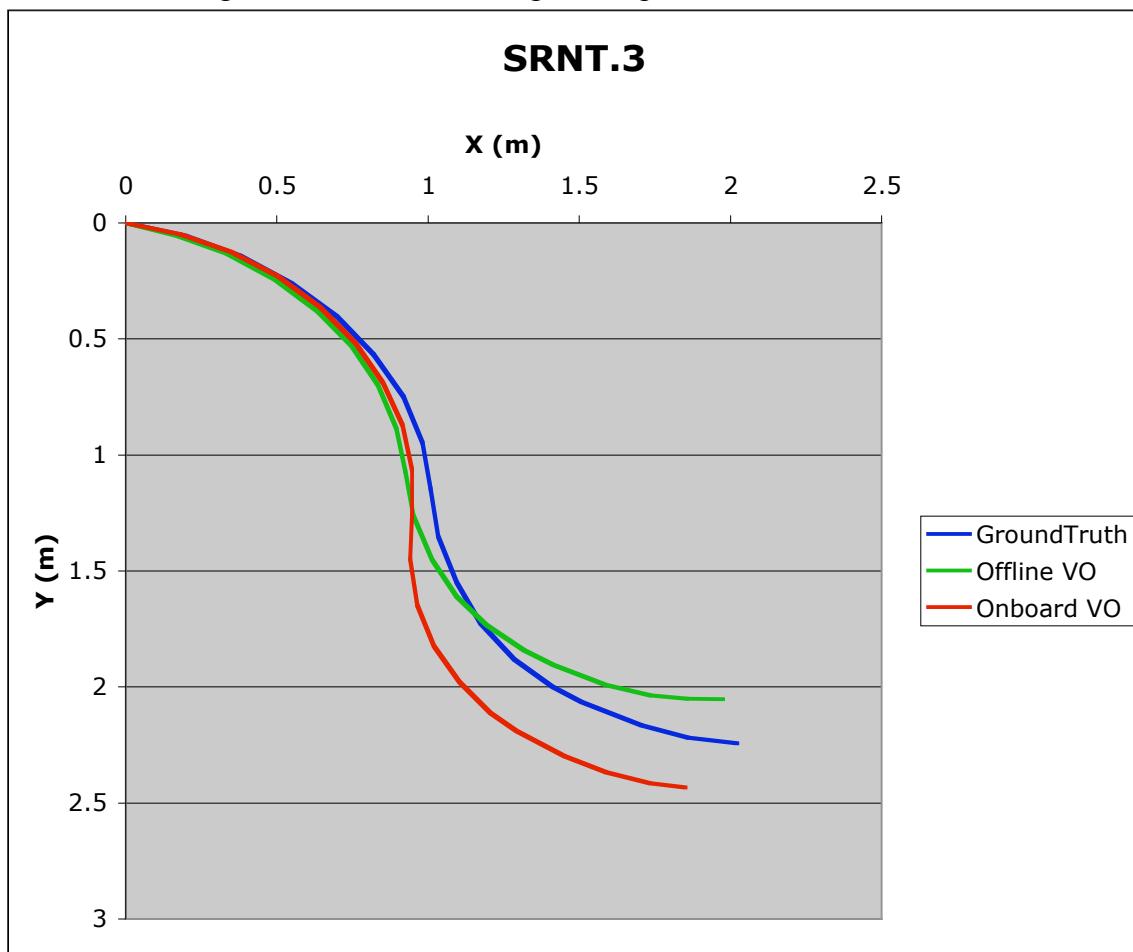


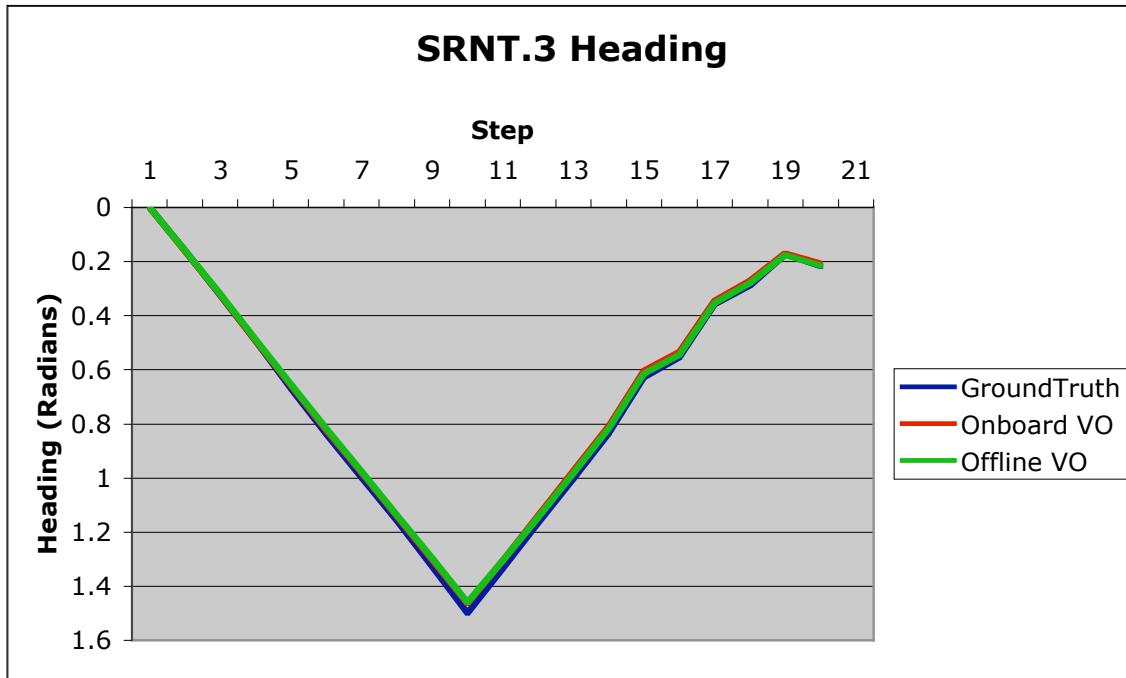


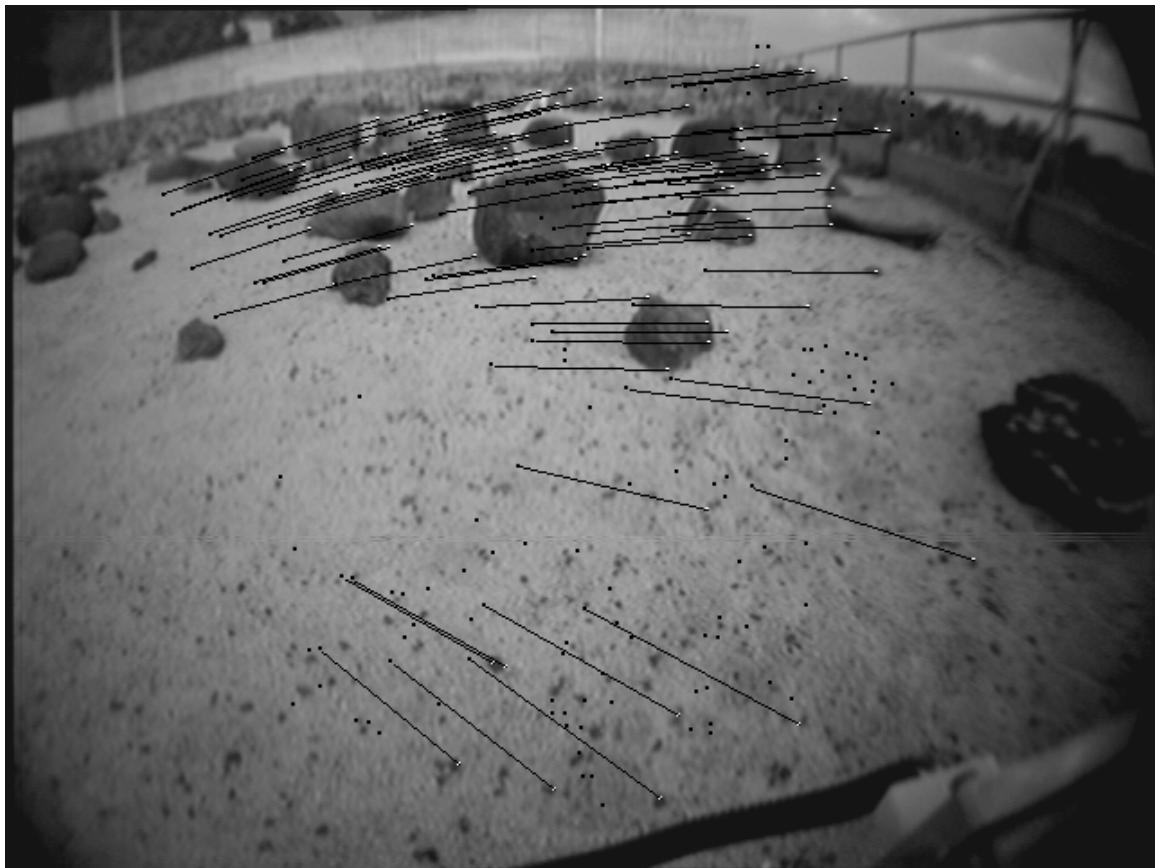
SRNT.3: S-Arc Drive

	Ground Truth	Onboard VO	Onboard Error	Offline VO*	Offline Error
X	2.022m	1.852m	-0.170m	1.975m	-0.047m
Y	2.244m	2.433m	0.189m	2.052m	-0.192m
Distance	3.277m	3.257m	7.75%	3.110m	6.03%
Heading	0.980°	11.877°	10.897°	2.811°	1.831°

*Failed: Too few features have small residuals in Schonemann outlier rejection for Steps 10 and 11, and algorithm failed to converge in Step 12.







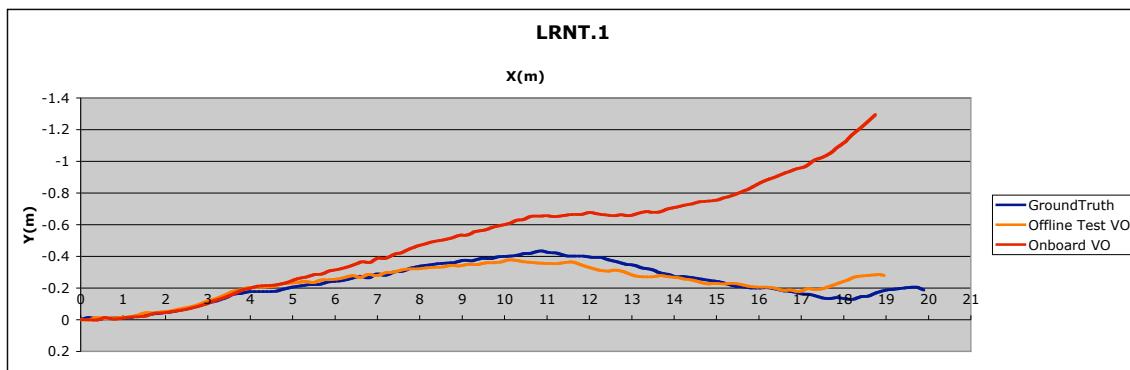
Long Range Navigation Tests (LRNT)

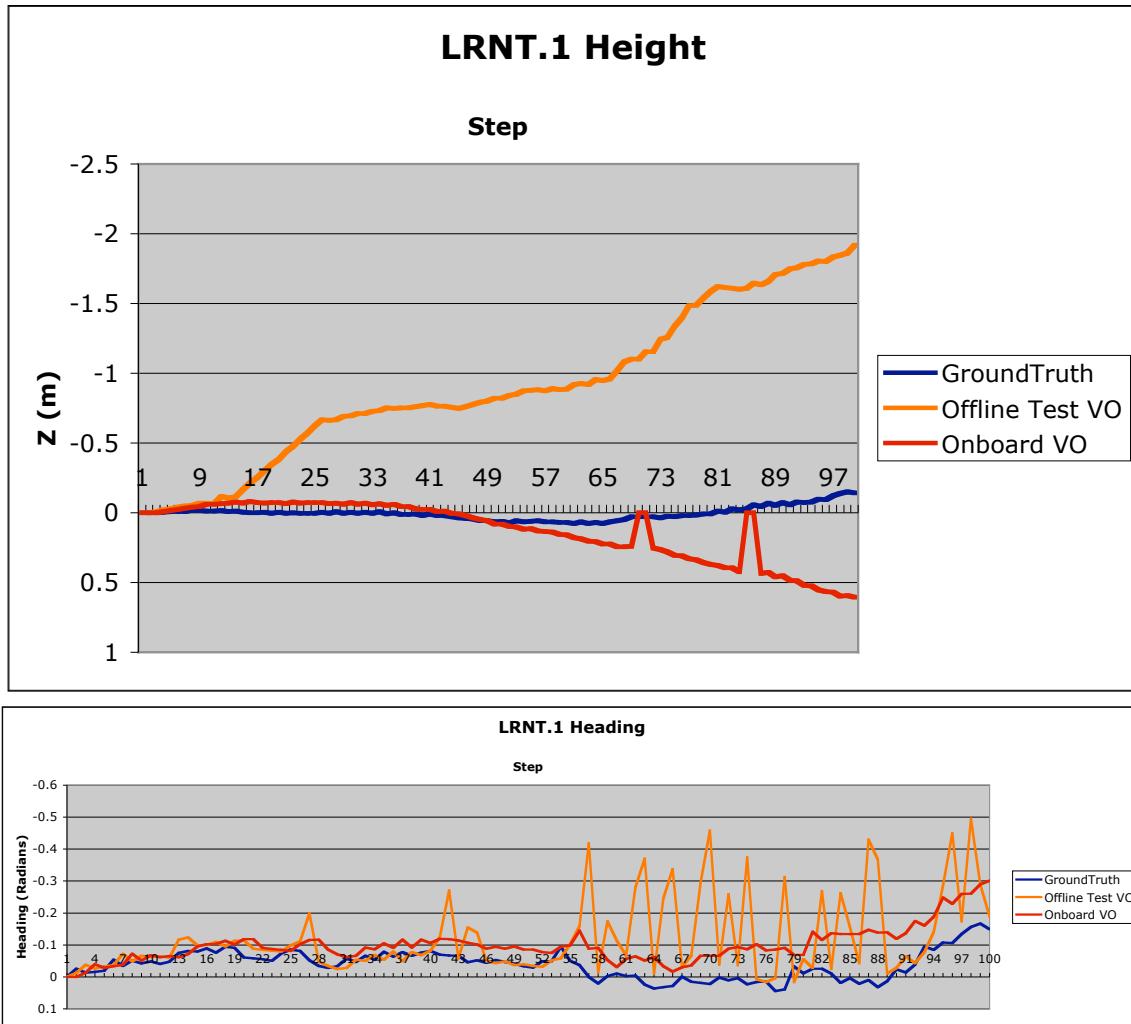
This series was designed to test VO behavior for the types of sequential drive and turn sequences typically seen during obstacle avoidance navigation. The order of results (green is rover odometry, blue is VO) is Gyro Yaw Bias, Heading, X position, and Y position, followed by the summary table.

LRNT.1: Straight Drive - Level Terrain

	Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	19.892	18.750	-1.142	*	*	18.950	-0.942
Y	-0.189	-1.295	-1.106	*	*	-0.279	-0.090
Distance	19.893	18.795	-7.99%	*	*	18.952	-4.73%
Heading	-8.569°	-17.286°	-8.717°	*	*	-10.813°	-2.244°

*Failed: Two few (min threshold of 8) features found in all images



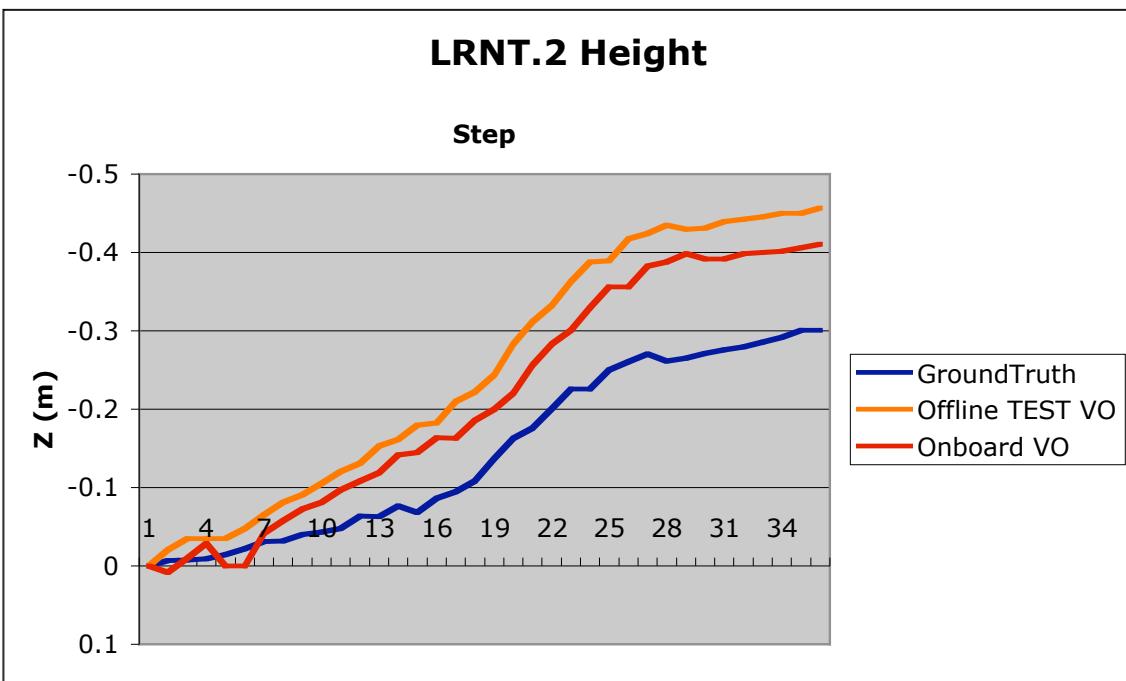
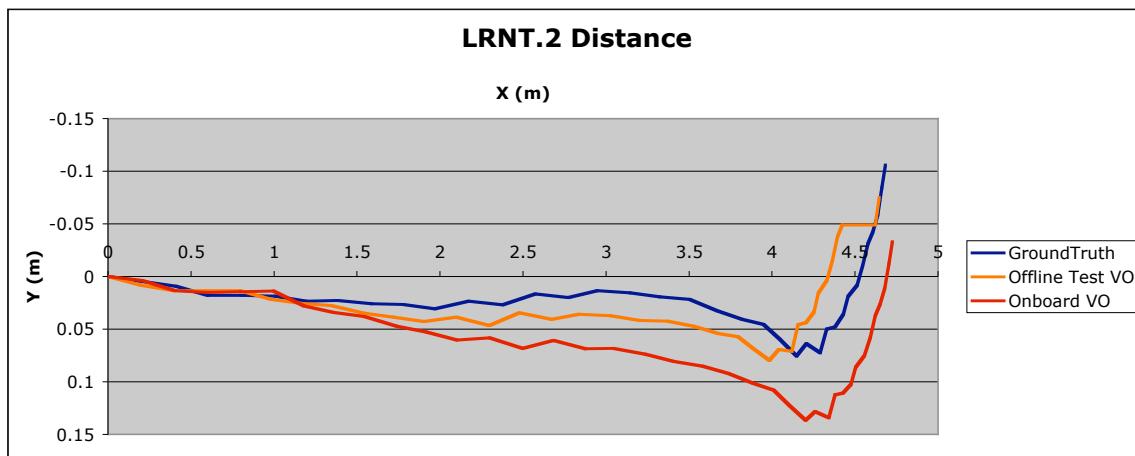


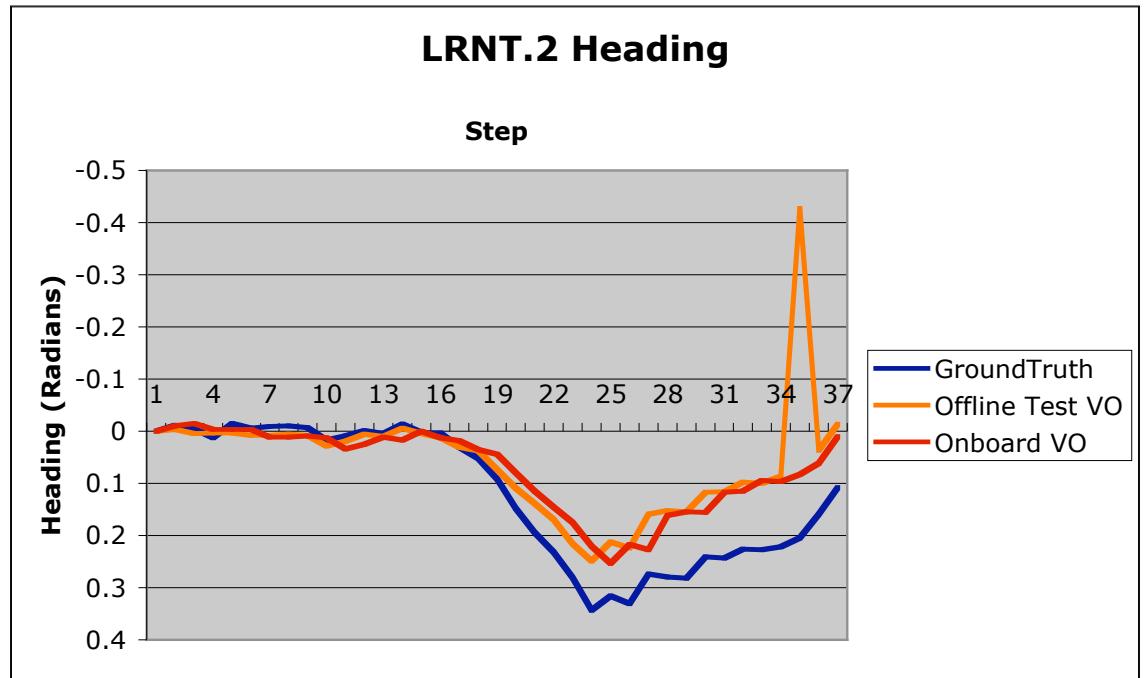


LRNT.2: Straight Drive – Mixed Slope Terrain

	Ground Truth	Onboard	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	4.892	4.879	-0.013	*	*	4.851	-0.041
Y	-0.110	0.011	0.121	*	*	-0.070	0.040
Distance	4.893	4.879	2.47%	*	*	4.851	1.16%
Heading	-6.171°	3.518°	9.689°	*	*	-2.989°	3.182°

*Failed: Two few (min threshold of 8) features found in all images





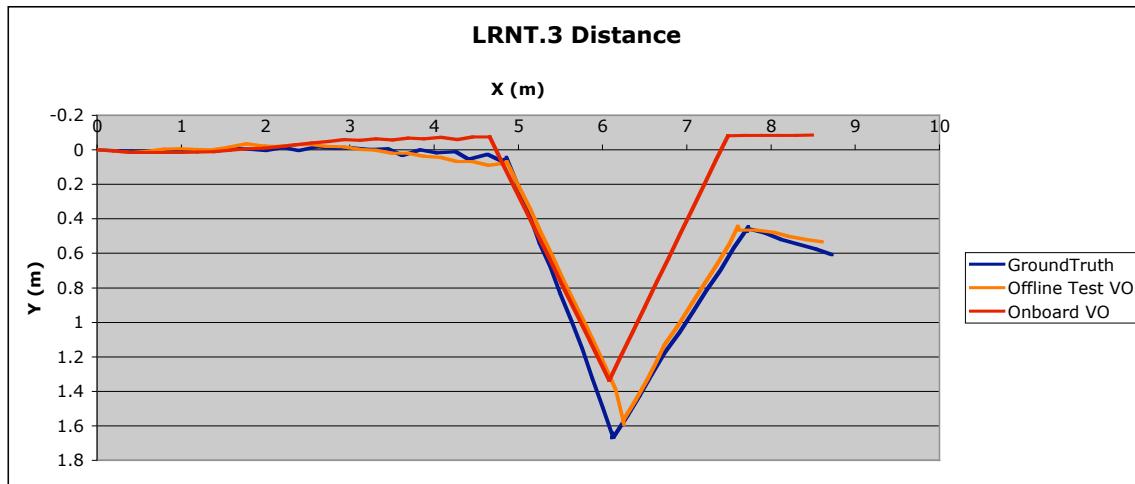


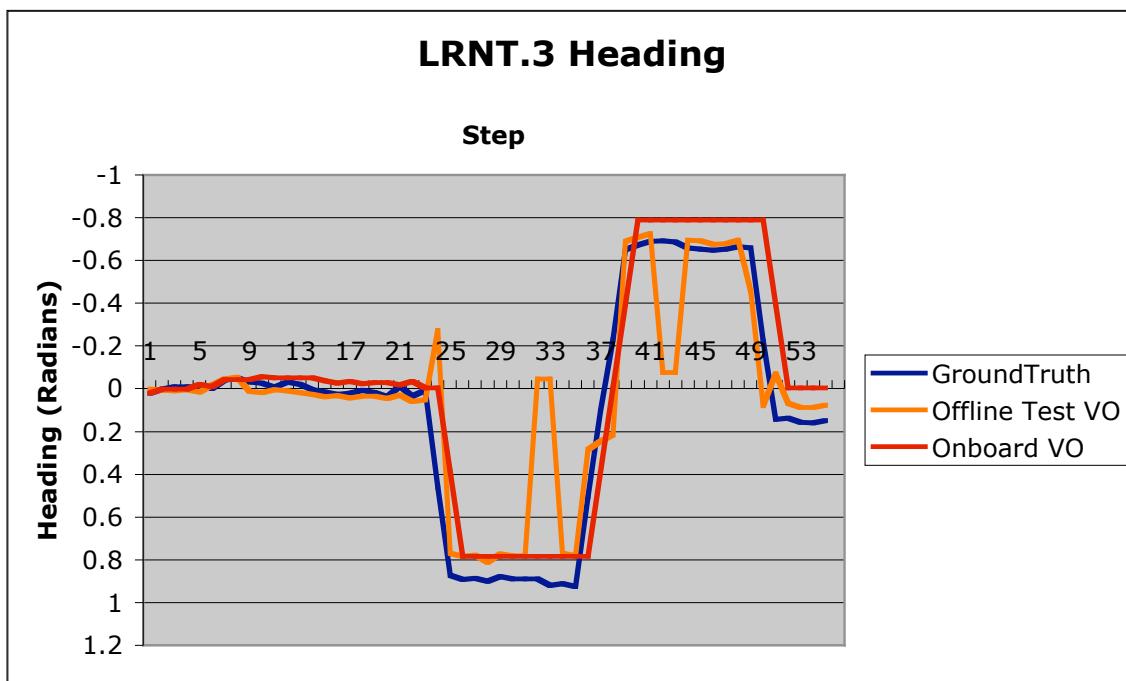
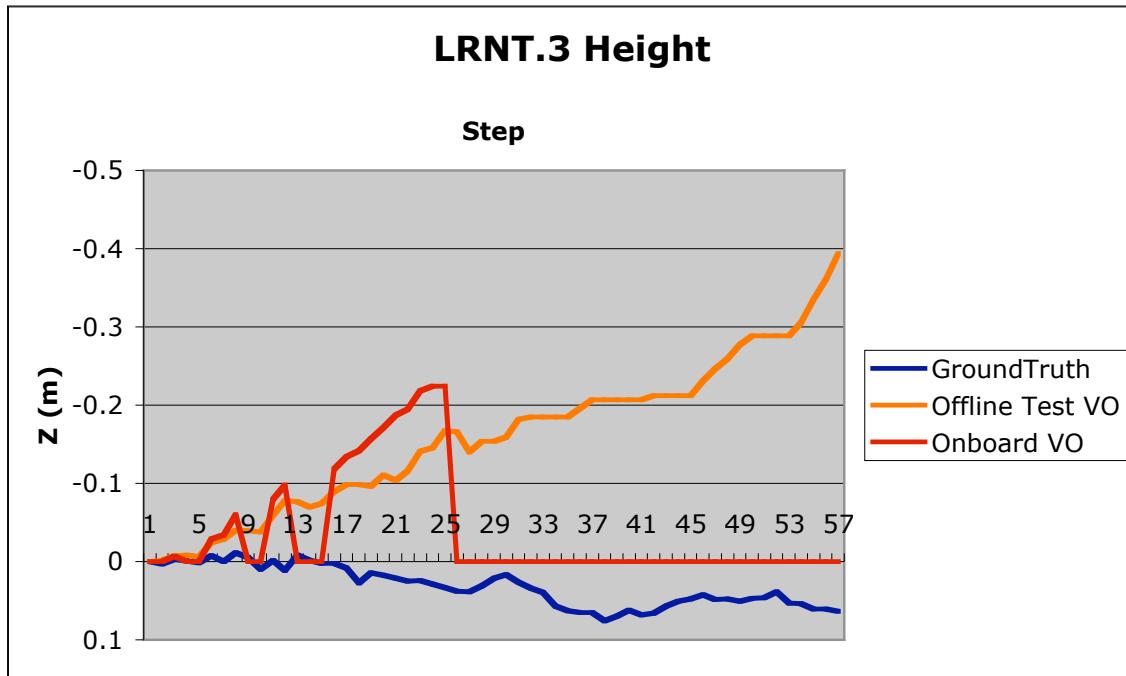
LRNT.3: Zig-Zag Drive

	Ground Truth	Onboard †	Onboard Error	Offline MER	Offline MER Error	Offline Test-Derived	Offline Test-Derived Error
X	8.726	8.489	-0.237	*	*	8.607	-0.119
Y	0.608	-0.085	-0.693	*	*	0.534	-0.074
Linear Distance	8.747	8.489	8.38%	*	*	8.623	1.60%
Total Distance	10.111	9.665	7.58%	*	*	9.759	1.39%
Heading	9.232°	-0.154°	-9.386°	*	*	4.358°	-4.874°

†Singular matrix during run led to tracking failure after step 24.

*Two few (min threshold of 8) features found in all images













Appendix A

Table A1. Description of parameter settings for visual odometry

Parameter Name	Description
Max_num_features	Upper bound on the number of features detected in the image using a desired feature detector
Min_num_features	Lower bound on the number of features detected in the image using a desired feature detector
Max_iterations	Upper bound on the number of iterations of the correlation matching step of the algorithm
Coor_window_rows	Vertical size of the correlation window used to match feature points across images
Coor_window_cols	Horizontal size of the correlation window used to match feature points across images
Track_window_size	Size of search window used to detect matching feature points across images
Max_nonrigid_fraction	Maximum fraction of matched points that are allowed to fail the rigidity test across images
Schonemann iterations	Maximum number of iterations allowed for convergence of the Schonemann outlier rejection algorithm used to prune bad matches
Min_features_Schonemann	Lower bound on the number of features that survive the Schonemann outlier rejection step
Max_stereo_gap	Upper bound on gap between candidate features prior to determination of 3D coordinate and correlation
Min_dist_feature	Lower bound on the distance of the detected features from the rover
Max_dist_feature	Upper bound on the distance of the detected features from the rover
Border_buffer	Size of outer border around search window for feature matching across images
Num_pyramid_level	Number of spatial sub-sampling pyramid levels
Affine_match_flag	Boolean flag for selection of correlation matching or affine matching of feature points across images
Min_correlation	Lower bound on the correlation score for matching of feature points across images
Max_mis_alignment	Upper bound on the misalignment of epipolar lines for feature matching across image pairs

Table A2. MER default parameter settings for visual odometry

Parameter Name	Default Value	Range	Units
Max_num_features	600	0:10,000	Features
Min_num_features	8	0:10,000	Features
Max_iterations	50	0:1,000	Iterations
Coor_window_rows	9	1:50	Pixels
Coor_window_cols	9	1:50	Pixels
Track_window_size	50	1:200	Pixels
Max_nonrigid_fraction	0.1	0:1	Fraction
Schonemann_iterations	20	0:10,000	Iterations
Min_features_Schonemann	8	6:20	Features
Max_stereo_gap	1	0:5	Pixels
Min_dist_feature	2.0	0.0:5.0	Meters
Max_dist_feature	20.0	5.0:100.0	Meters
Border_buffer	5	0:30	Pixels
Num_pyramid_level	3	1:3	Pyramid levels
Affine_match_flag	0	0:1	Boolean
Min_correlation	0.6	0.0:1.0	Norm. correlation score
Max_mis_alignment	2	0:50	Pixels

Table A3. Test-derived parameter settings for visual odometry

Parameter Name	Default Value	Range	Units
Max_num_features	200	0:10,000	Features
Min_num_features	8	0:10,000	Features
Max_iterations	50	0:1,000	Iterations
Coor_window_rows	11	1:50	Pixels
Coor_window_cols	11	1:50	Pixels
Track_window_size	50	1:200	Pixels
Max_nonrigid_fraction	0.1	0:1	Fraction
Schonemann_iterations	20	0:10,000	Iterations
Min_features_Schonemann	8	6:20	Features
Max_stereo_gap	2	0:5	Pixels
Min_dist_feature	0.5	0.0:5.0	Meters
Max_dist_feature	20.0	5.0:100.0	Meters
Border_buffer	10	0:30	Pixels
Num_pyramid_level	2	1:3	Pyramid levels
Affine_match_flag	0	0:1	Boolean
Min_correlation	0.85	0.0:1.0	Norm. correlation score
Max_mis_alignment	3	0:50	Pixels

Tabel A4. Default CLARAty parameter settings for visual odometry

Parameter Name	Default Value	Range	Units
Max_num_features*	200	0:10,000	Features
Min_num_features	8	0:10,000	Features
Max_iterations	50	0:1,000	Iterations
Coor_window_rows*	9	1:50	Pixels
Coor_window_cols*	9	1:50	Pixels
Track_window_size	50	1:200	Pixels
Max_nonrigid_fraction	0.1	0:1	Fraction
Schonemann_iterations	20	0:10,000	Iterations
Min_features_Schonemann	8	6:20	Features
Max_stereo_gap	2	0:5	Pixels
Min_dist_feature	0.5	0.0:5.0	Meters
Max_dist_feature	20.0	5.0:100.0	Meters
Border_buffer	20	0:30	Pixels
Num_pyramid_level	2	1:3	Pyramid levels
Affine_match_flag	1	0:1	Boolean
Min_correlation	0.70	0.0:1.0	Norm. correlation score
Max_mis_alignment	3	0:50	Pixels

*Parameters that can be set through the interface.

Appendix B

Model = CAHVOR = perspective, distortion

FIDO Right Front HazCam

Dimensions = 640 480 15.29 7.19 569.45 389.11

Performing least-square adjustment:

Q = 2.25177e+06

Q = 22455.1

Q = 5122.56

Q = 94.5306

Q = 88.8848

Q = 88.6285

Rejecting worst point:

Performing least-square adjustment:

Q = 2.24563e+06

Q = 21745.4

Q = 4947.59

Q = 90.3697

Q = 86.5827

Q = 86.3376

C = 0.607371 0.061995 -0.414739

A = 0.858452 0.005637 0.512863

H = 233.056010 337.654917 146.451300

V = 30.399922 -3.864531 407.324430

O = 0.858940 0.011112 0.511956

R = 0.000024 -0.268550 0.057314

Sigma = 0.394667

Rejected points: 0

S =

1.5340676e-07 7.1144798e-09 3.5079145e-08 -3.1284803e-08 -3.2575480e-10
5.2369599e-08 -7.3121550e-06 -5.9029075e-05 1.4789091e-05 1.2543359e-05
1.5403445e-06 -6.0834861e-05 -1.7857862e-08 7.1971019e-09 2.9805011e-08
7.0819791e-11 8.9316359e-08 -4.4636772e-08

7.1144798e-09 4.0217177e-08 1.3675562e-09 -2.2001385e-09 3.6637050e-08
3.2798938e-09 1.0042559e-05 9.7862680e-06 1.4288996e-05 -1.1533731e-06
7.2522713e-06 -1.7194913e-07 -1.3580679e-09 9.9341656e-10 2.2569493e-09 -
1.9421838e-10 -1.3121565e-08 8.6831221e-09

3.5079145e-08 1.3675562e-09 4.4661887e-08 -5.3820002e-09 -5.0531030e-09
9.0642087e-09 -8.0454942e-07 -2.0453222e-05 1.5639340e-06 1.4735398e-05 -
5.1847597e-07 -1.0107673e-05 9.5685693e-09 -2.3586247e-09 -1.6002584e-08
4.5470550e-11 2.4237970e-08 -1.2010622e-08

-3.1284803e-08 -2.2001385e-09 -5.3820002e-09 2.1000205e-07 -8.4410751e-08 -
3.5058355e-07 6.2694211e-05 -1.2829714e-05 -1.0886480e-04 6.2136878e-05 -
1.2258338e-05 -7.4753925e-05 2.1538169e-07 -8.9843856e-08 -3.5940893e-07
4.9891810e-08 -6.6505657e-08 2.9366001e-08

-3.2575480e-10 3.6637050e-08 -5.0531030e-09 -8.4410751e-08 1.3878230e-06
1.2603244e-07 -4.7799619e-05 2.2155271e-04 8.1828956e-05 4.7798857e-05
2.9229064e-04 -8.0198752e-05 -1.1051911e-07 1.4213712e-06 1.5456816e-07
5.4608954e-07 -3.6725821e-07 1.8744475e-07

5.2369599e-08 3.2798938e-09 9.0642087e-09 -3.5058355e-07 1.2603244e-07
5.8543807e-07 -1.0441508e-04 1.9039144e-05 1.8132351e-04 -1.0453324e-04
1.7305022e-05 1.2600848e-04 -3.5930121e-07 1.3475779e-07 5.9989668e-07 -
8.9515288e-08 1.1535820e-07 -5.1215089e-08

-7.3121550e-06 1.0042559e-05 -8.0454942e-07 6.2694211e-05 -4.7799619e-05 -
1.0441508e-04 2.8937740e-02 -2.2536134e-01 -3.3750669e-02 1.2760356e-01 -
5.9593509e-03 -2.0654186e-01 6.0357477e-05 -7.7817470e-05 -9.9576173e-05
6.4976994e-04 -1.7786212e-04 3.9134130e-05

-5.9029075e-05 9.7862680e-06 -2.0453222e-05 -1.2829714e-05 2.2155271e-04
1.9039144e-05 -2.2536134e-01 1.1320320e+01 1.3305642e-01 -5.7298906e+00 -
1.3158740e-01 9.6326597e+00 -8.7884699e-07 4.1673649e-04 -7.5724702e-06 -
3.3355962e-02 8.7438972e-03 -1.7904772e-03

1.4789091e-05 1.4288996e-05 1.5639340e-06 -1.0886480e-04 8.1828956e-05
1.8132351e-04 -3.3750669e-02 1.3305642e-01 6.9448287e-02 -9.1019862e-02
1.2555564e-02 1.3863069e-01 -1.0604197e-04 7.6249332e-05 1.7625795e-04 -
3.6463213e-04 1.0713542e-04 -2.4307005e-05

1.2543359e-05 -1.1533731e-06 1.4735398e-05 6.2136878e-05 4.7798857e-05 -
1.0453324e-04 1.2760356e-01 -5.7298906e+00 -9.1019862e-02 2.9449278e+00
1.0277090e-01 -4.9320773e+00 6.7100603e-05 -4.5031461e-05 -1.1160129e-04
1.7060550e-02 -4.5362091e-03 9.5315567e-04

1.5403445e-06 7.2522713e-06 -5.1847597e-07 -1.2258338e-05 2.9229064e-04
1.7305022e-05 -5.9593509e-03 -1.3158740e-01 1.2555564e-02 1.0277090e-01
6.7317265e-02 -1.7248018e-01 -1.3486489e-05 3.0510421e-04 1.6003595e-05
6.4533039e-04 -2.2435138e-04 7.1648099e-05

-6.0834861e-05 -1.7194913e-07 -1.0107673e-05 -7.4753925e-05 -8.0198752e-05
1.2600848e-04 -2.0654186e-01 9.6326597e+00 1.3863069e-01 -4.9320773e+00 -
1.7248018e-01 8.2941948e+00 -6.3150420e-05 7.8216496e-05 1.0425341e-04 -
2.8636089e-02 7.5694066e-03 -1.5778648e-03

-1.7857862e-08 -1.3580679e-09 9.5685693e-09 2.1538169e-07 -1.1051911e-07 -
3.5930121e-07 6.0357477e-05 -8.7884699e-07 -1.0604197e-04 6.7100603e-05 -
1.3486489e-05 -6.3150420e-05 3.1206273e-07 -8.0020468e-08 -5.2183001e-07
3.5688030e-10 -1.5137971e-07 7.0602665e-08

7.1971019e-09 9.9341656e-10 -2.3586247e-09 -8.9843856e-08 1.4213712e-06
1.3475779e-07 -7.7817470e-05 4.1673649e-04 7.6249332e-05 -4.5031461e-05
3.0510421e-04 7.8216496e-05 -8.0020468e-08 1.6377818e-06 9.8700610e-08
1.2132706e-09 -2.8937328e-07 1.8082372e-07

2.9805011e-08 2.2569493e-09 -1.6002584e-08 -3.5940893e-07 1.5456816e-07
5.9989668e-07 -9.9576173e-05 -7.5724702e-06 1.7625795e-04 -1.1160129e-04
1.6003595e-05 1.0425341e-04 -5.2183001e-07 9.8700610e-08 8.7336420e-07 -
6.2509943e-10 2.6026124e-07 -1.2238003e-07

7.0819790e-11 -1.9421838e-10 4.5470550e-11 4.9891810e-08 5.4608954e-07 -
8.9515288e-08 6.4976994e-04 -3.3355962e-02 -3.6463213e-04 1.7060550e-02
6.4533039e-04 -2.8636089e-02 3.5688030e-10 1.2132706e-09 -6.2509943e-10
9.9707839e-05 -2.6775001e-05 5.7139082e-06

8.9316359e-08 -1.3121565e-08 2.4237970e-08 -6.6505657e-08 -3.6725821e-07
1.1535820e-07 -1.7786212e-04 8.7438972e-03 1.0713542e-04 -4.5362091e-03 -
2.2435138e-04 7.5694066e-03 -1.5137971e-07 -2.8937328e-07 2.6026124e-07 -
2.6775001e-05 8.1241406e-06 -2.0407318e-06

-4.4636772e-08 8.6831221e-09 -1.2010622e-08 2.9366001e-08 1.8744475e-07 -
5.1215089e-08 3.9134130e-05 -1.7904772e-03 -2.4307005e-05 9.5315567e-04
7.1648099e-05 -1.5778648e-03 7.0602665e-08 1.8082372e-07 -1.2238003e-07
5.7139082e-06 -2.0407318e-06 6.1549139e-07

Hs = 336.155401

Hc = 277.080271

Vs = 334.123175

Vc = 234.976563

Theta = -1.567895 (-89.833787 deg)

S internal =

1.1309011e+01 -1.1657892e-01 1.1242169e+01 1.4841885e-02 2.2578844e-06
-1.1657892e-01 1.6777600e-01 -1.0432985e-01 1.7528028e-02 2.6683791e-05
1.1242169e+01 -1.0432985e-01 1.1188407e+01 2.4612050e-02 -3.9879344e-08
1.4841885e-02 1.7528028e-02 2.4612050e-02 7.7774822e-02 9.1948054e-06
2.2578844e-06 2.6683791e-05 -3.9879344e-08 9.1948054e-06 1.0601844e-07

Model = CAHVOR = perspective, distortion

FIDO Left Front HazCam

Dimensions = 640 480 26.66 16.97 556.64 450.59

Performing least-square adjustment:

Q = 899382

Q = 27788.5

Q = 6222.9

Q = 45.3337

Q = 31.2952

Q = 30.3507

Rejecting worst point:

Performing least-square adjustment:

Q = 897669

Q = 26029.7

Q = 5821.59

Q = 40.9776

Q = 30.3694

Q = 29.4983

C = 0.607362 -0.057956 -0.414557

A = 0.860190 -0.004264 0.509956

H = 248.057368 338.565755 151.632959

VO Test Report

V = 22.679155 -4.366883 406.007868

O = 0.860596 0.004544 0.509269

R = 0.000070 -0.283891 0.069514

Sigma = 0.239982

Rejected points: 0

S =

5.4159307e-08 -4.4867100e-10 1.3353051e-08 -1.0535664e-08 3.3604931e-10
1.7773962e-08 -3.8934336e-06 -2.2239379e-05 4.6637385e-06 5.2361533e-06
9.1499134e-07 -2.2550486e-05 -5.9326416e-09 9.2944435e-09 9.9417319e-09
8.7340512e-11 3.8777734e-08 -2.5012883e-08

-4.4867100e-10 1.4213921e-08 -3.4106834e-10 -1.3968170e-12 1.6893702e-08
1.4298132e-10 3.6233026e-06 6.5670716e-06 4.9190673e-06 -8.7502720e-07
3.4466513e-06 1.7137522e-06 7.8732600e-10 6.2496943e-09 -1.3864935e-09 -
9.2775458e-11 -1.1602463e-08 7.4266701e-09

1.3353051e-08 -3.4106834e-10 1.6435564e-08 -6.1627370e-09 1.9303213e-09
1.0411143e-08 -2.0975916e-06 -6.6083733e-06 2.8209141e-06 4.2069571e-06
5.4399520e-07 -2.0093307e-06 -7.0914445e-10 5.0904570e-09 1.1526692e-09
3.6565399e-11 5.7477943e-09 -3.8641179e-09

-1.0535664e-08 -1.3968170e-12 -6.1627370e-09 9.6320439e-08 5.8492364e-09 -
1.6242102e-07 2.8662725e-05 -9.9507512e-07 -4.8756702e-05 2.9808938e-05
2.6508592e-06 -3.8115621e-05 1.0420176e-07 4.5060526e-09 -1.7612261e-07
4.2385031e-08 -5.0714814e-08 2.6540527e-08

3.3604931e-10 1.6893702e-08 1.9303213e-09 5.8492364e-09 5.2877449e-07 -
5.4646903e-09 -3.2623096e-06 -1.3387124e-04 -1.2003613e-07 1.4675646e-04
1.1573788e-04 -2.4336183e-04 1.8627289e-09 5.6207522e-07 -8.1890146e-09
8.5486840e-07 -2.6013237e-07 7.3010071e-08

1.7773962e-08 1.4298132e-10 1.0411143e-08 -1.6242102e-07 -5.4646903e-09
2.7392022e-07 -4.8374369e-05 5.6409503e-07 8.2239983e-05 -4.9058983e-05 -

3.5079541e-06 6.2266231e-05 -1.7574813e-07 -2.9218587e-09 2.9700887e-07 -
6.4377457e-08 8.3378478e-08 -4.4159824e-08

-3.8934336e-06 3.6233026e-06 -2.0975916e-06 2.8662725e-05 -3.2623096e-06 -
4.8374369e-05 1.1656262e-02 -1.1088420e-01 -1.4513700e-02 6.4111231e-02
6.5237738e-04 -1.0458390e-01 3.0963296e-05 -1.5014952e-05 -5.2187719e-05
3.3608892e-04 -1.1094688e-04 3.3048654e-05

-2.2239379e-05 6.5670716e-06 -6.6083733e-06 -9.9507512e-07 -1.3387124e-04
5.6409503e-07 -1.1088420e-01 1.1091986e+01 8.6568451e-02 -5.6309360e+00 -
1.4415298e-01 9.5232347e+00 1.2335756e-05 1.6045576e-04 -2.2284357e-05 -
3.2698164e-02 9.1783139e-03 -2.2048247e-03

4.6637385e-06 4.9190673e-06 2.8209141e-06 -4.8756702e-05 -1.2003613e-07
8.2239983e-05 -1.4513700e-02 8.6568451e-02 2.8927980e-02 -5.8187718e-02 -
1.7337888e-03 9.2517753e-02 -5.1607292e-05 -3.1619900e-06 8.7235383e-05 -
2.7047519e-04 9.1874622e-05 -2.7744710e-05

5.2361533e-06 -8.7502720e-07 4.2069571e-06 2.9808938e-05 1.4675646e-04 -
4.9058983e-05 6.4111231e-02 -5.6309360e+00 -5.8187718e-02 2.8806052e+00
9.0543024e-02 -4.8639105e+00 2.7838152e-05 1.7825722e-06 -4.7057447e-05
1.6683010e-02 -4.7025651e-03 1.1370776e-03

9.1499134e-07 3.4466513e-06 5.4399520e-07 2.6508592e-06 1.1573788e-04 -
3.5079541e-06 6.5237738e-04 -1.4415298e-01 -1.7337888e-03 9.0543024e-02
2.7567915e-02 -1.5228791e-01 1.9386777e-06 1.2188400e-04 -4.3692122e-06
5.2331608e-04 -1.4947549e-04 3.7398915e-05

-2.2550486e-05 1.7137522e-06 -2.0093307e-06 -3.8115621e-05 -2.4336183e-04
6.2266231e-05 -1.0458390e-01 9.5232347e+00 9.2517753e-02 -4.8639105e+00 -
1.5228791e-01 8.2256394e+00 -2.6350192e-05 -2.7435684e-07 4.4529536e-05 -
2.8192605e-02 7.9228794e-03 -1.9067032e-03

-5.9326416e-09 7.8732600e-10 -7.0914445e-10 1.0420176e-07 1.8627289e-09 -
1.7574813e-07 3.0963296e-05 1.2335756e-05 -5.1607292e-05 2.7838152e-05
1.9386777e-06 -2.6350192e-05 1.3669277e-07 5.2600139e-10 -2.3099087e-07
3.7162517e-11 -6.2477413e-08 3.7275028e-08

9.2944435e-09 6.2496943e-09 5.0904570e-09 4.5060526e-09 5.6207522e-07 -
2.9218587e-09 -1.5014952e-05 1.6045576e-04 -3.1619900e-06 1.7825722e-06
1.2188400e-04 -2.7435684e-07 5.2600139e-10 6.7129739e-07 -6.9098162e-09
9.6282307e-10 -3.7681779e-09 3.3788493e-09

9.9417319e-09 -1.3864935e-09 1.1526692e-09 -1.7612261e-07 -8.1890146e-09
2.9700887e-07 -5.2187719e-05 -2.2284357e-05 8.7235383e-05 -4.7057447e-05 -

4.3692122e-06 4.4529536e-05 -2.3099087e-07 -6.9098162e-09 3.9039492e-07 -
7.1433663e-11 1.0560937e-07 -6.3018385e-08

8.7340512e-11 -9.2775458e-11 3.6565399e-11 4.2385031e-08 8.5486840e-07 -
6.4377457e-08 3.3608892e-04 -3.2698164e-02 -2.7047519e-04 1.6683010e-02
5.2331608e-04 -2.8192605e-02 3.7162517e-11 9.6282307e-10 -7.1433664e-11
9.6973551e-05 -2.7523032e-05 6.7370278e-06

3.8777734e-08 -1.1602463e-08 5.7477943e-09 -5.0714814e-08 -2.6013237e-07
8.3378478e-08 -1.1094688e-04 9.1783139e-03 9.1874622e-05 -4.7025651e-03 -
1.4947549e-04 7.9228794e-03 -6.2477413e-08 -3.7681779e-09 1.0560937e-07 -
2.7523032e-05 8.5358651e-06 -2.4120311e-06

-2.5012883e-08 7.4266701e-09 -3.8641179e-09 2.6540527e-08 7.3010071e-08 -
4.4159824e-08 3.3048654e-05 -2.2048247e-03 -2.7744710e-05 1.1370776e-03
3.7398915e-05 -1.9067032e-03 3.7275028e-08 3.3788493e-09 -6.3018385e-08
6.7370278e-06 -2.4120311e-06 8.2865698e-07

Hs = 339.825078

Hc = 289.258879

Vs = 337.698665

Vc = 226.573199

Theta = -1.569288 (-89.913566 deg)

S internal =

1.1214541e+01 -1.9527886e-01 1.1145895e+01 1.4976585e-02 -1.5888653e-06
-1.9527886e-01 6.3534994e-02 -1.9297968e-01 -3.1391699e-04 2.8467847e-06
1.1145895e+01 -1.9297968e-01 1.1081304e+01 1.7836170e-02 -1.6823576e-06
1.4976585e-02 -3.1391699e-04 1.7836170e-02 3.7394590e-02 7.5549035e-07
-1.5888653e-06 2.8467847e-06 -1.6823576e-06 7.5549035e-07 2.9424361e-08